An investigation on using solid waste materials as aggregate substitute in cementitious concrete composites

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AN INVESTIGATION ON USING SOLID WASTE MATERIALS AS AGGREGATE SUBSTITUTE IN CEMENTITIOUS CONCRETE COMPOSITES

A Dissertation

Submitted

In Partial Fulfillment

of the Requirements for the Degree

Doctor of Industrial Technology

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

AN INVESTIGATION ON USING SOLID WASTE MATERIALS AS AGGREGATE SUBSTITUTE IN CEMENTITIOUS CONCRETE COMPOSITES

An Abstract of a Dissertation

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ABSTRACT

The problem of disposing and managing solid waste materials in the United States and other industrial countries has become one of the major environmental, economical, and social issues. A complete waste management system including source reduction, reuse, recycling, landfilling, and incineration needs to be implemented to control the increasing waste disposal problems. Of the above options, recycling is the most promising waste management process to the disposal of materials in the waste stream. One of the most promising markets to utilize recycled waste materials successfully on an open-loop basis is the construction industry.

The purpose of this research study was to evaluate the possibility of using different granulated solid waste materials (plastics, fiberglass, and glass) from different sources as partial aggregate substitutes to the fine aggregate (sand) in a portland cement concrete mixture to produce new concrete composites. Three different types of concrete composites containing one of these aggregate waste materials were prepared. Four different volume percentages of aggregate substitute (5, 10, 15, and 20%) were utilized for each additive. A control cementitious concrete composite was also prepared as a reference for the new concrete composites. Three different test methods were conducted on these cementitious concrete composites: compression strength test, splitting tensile strength test, and flexure test. Standard ASTM procedures were followed in casting of and testing all the flexural beams and concrete cylinders and the curing of 28-day concrete samples.

Statistical procedures of the data obtained were used to determine any significant differences among the values of the mechanical properties of the tested concrete composites. Graphical representation and analysis of the calculated results were also performed to compare the developed cementitious concrete composites with the control specimens. Furthermore, a scanning electron microscope (SEM) was used to study the relationship between these mechanical properties and the microstructure and interfacial features of the new concrete composites. Optical photographs were also obtained to show the general fracture behaviors of these composites.

The main findings of this investigation revealed that increasing the volume percentage of plastics aggregate substitute to the cementitious concrete composite led, in general, to a slight reduction of the compressive, splitting tensile, and flexural strengths. On the other hand, the stiffness of these plastics-containing concrete composites was almost the same as that of the control one. In case of glass-containing concrete composites, the average values of compressive and splitting tensile strengths of these composites were comparable to those of the control one. On the other hand, the values of the modulus of rupture and elasticity of all the tested glass-containing concrete composites were almost the same as (and in some cases especially at 20% glass aggregate substitute higher than) those of the control one. In case of fiberglass-containing concrete composites, adding more volume percentages of this aggregate substitute to the cementitious concrete composite led to reducing the compressive, splitting tensile, and flexural strengths of the cementitious concrete composite. On the other hand, adding more volume percentage of fiberglass aggregate substitute to the cementitious concrete composite led to an increase in the stiffness of this composite. Based on the present research study, it is believed that the visual analysis technique should be strongly recommended to compare the properties of different types of concrete composites qualitatively. This technique may also be used to predict whether different concrete composites have the same brittle or ductile fracture modes under different loading systems.

CHAPTER I

INTRODUCTION

Solid Waste Crisis

Solid waste disposal and management has become one of the major environmental issues in many countries such as the United States, Germany, and Japan (Basta, Fouhy, Gilges, Shanley, & Ushio, 1990). There is a strong movement in most of the industrialized countries in the world to decrease the amount of waste generated and to use their resources more efficiently. In addition, disposal costs (including tipping fees) have risen dramatically as landfills are reaching capacity or being closed because of failure to meet environmental safety standards. Hence, finding new waste management facilities has become extremely difficult due to environmental, political, and societal concerns.

Basta et al.(1990) stated that the amount of municipal solid waste (MSW) generated per year in the United States is greater than that generated in the European Community (approximately 180 million tons versus about 110 million tons respectively). The major solid waste materials in the MSW in the U.S. (in descending order by weight) are paper, compost, metals, glass, and plastics (Reinfield, 1992). However, some of these materials have higher volume/weight ratio than others. For example, although plastic materials are lighter in weight compared to paper, metals and glass, they occupy more space in landfills and transportation facilities. On the other hand, the ranking of the solid waste materials in the MSW in the U.S. according to their volume is different and in the following order: paper, plastics, compost, metals, and glass (Hoffer & Nunes, 1992). This shows that both the weight and volume of the waste materials are important factors when any solution to the waste problems is to be regarded.

Carless (1992) pointed out that most experts in the U.S. believe that to control the increasing waste disposal problems, an integrated waste management approach should be implemented. This approach involves source reduction, reuse, recycling, and either landfilling or incineration as a final disposal method. One of the main obstacles to reduce wastes is the public's demand for convenience and disposable products (Hanson, 1989). According to the Office of Solid Waste (1990), there are three main methods to handle the

MSW: landfilling, incineration, and recycling. The order of distribution of the total MSW treated by such methods is 73%, 14%, and 13% respectively. Landfilling and incineration options are not viable environmentally, socially, and economically (Bell, 1990). Recycling is the most promising solution to the disposal of materials in the waste stream.

Recycling (or waste management) can be very powerful if some of the associated problems can be solved. Some of these problems are collecting and sorting the waste materials; processing such used materials into useful products; and most importantly marketing the recycled products (U.S. Documents, 1992). Yet, the success of any recycling program depends basically upon the roles of the industrial manufacturers, citizens, environmental officials, community groups and legislators in increasing recycling and consequently minimizing the solid wastes in landfills. They should all look at the generated waste, as Reinfield (1992) stated, not only as the fastest-growing resource in the U.S. but also as the fastest growing opportunity.

Solid Waste Materials

As mentioned above, the major solid waste materials in the U.S. (MSW) are paper, compost, metals, glass, and plastics (Reinfield, 1992). Two of such materials are commonly being used in the construction industry (which is one of the largest industries worldwide). These materials are glass and plastics; mostly in the form of fiber reinforcements for the concrete mixes. The common practice to use these materials in the construction industry is in their virgin forms and rarely their recyclable forms are used instead. Examples of using such materials in concrete mixes can be found in the works of Fahmy, Egger, & Varzavand, 1989; Larralde, Silva-Rodriguez, & Burdette, 1994; Parviz, Atef, & Abdulrahman, 1993; Rebeiz, Fowler, & Paul, 1991; Vaverka, 1991. Since these two waste materials will be used in the present research study, it is appropriate now to introduce each one of them in more details:

Glass Waste

There are three standard types of glass in the waste stream: clear, green, and brown. Clear glass waste is generally having the highest value while brown glass waste is having the lowest value (Duston, 1993). The majority of these types of products are recyclable (examples are glass bottles and jars used for beverage and food packaging). The basic constituents of these products are almost pure silica sand melted in huge furnaces with some burnt lime or limestone and soda ash in addition to crushed glass (called cullet) to some extent. Other glass products are not easily recyclable (such as mirrors, drinking glasses. Pyrex, windows, and light bulbs). This is because the identification of the compositions of these products is difficult and expensive. So far, no widespread recycling programs have been established for these types of glass (Carless, 1992).

Broken glass of mixed colors is not acceptable by the majority of the glass manufacturers because of the difficulty to obtain a constant supply of high quality cullet which is also free of contaminants (Carless, 1992). Therefore, these waste materials can only be used to make products (such as roof shingles, fiberglass, and reflectors) in which light distortion or purity is not a problem (Reinfield, 1992). Mixed colored glass can also be used as a roadbed base (a substitute for stone) in glassphalt and as landfill cover (Duston, 1993). In general, recycling glass can reduce mining wastes by 80% because silica, soda ash, and limestone, the main raw materials in glass do not have to be added again when recycled glass is used. This can be translated into a significant energy savings (up to 32%) since a furnace containing pure cullet burns at a lower temperature than the one containing pure raw materials. Recycling glass can also reduce air pollution by 20% and water use by 50% (Carless, 1992). However, some of the major problems with recycling glass in industry are the uncertainty of supplying recyclers with constant and high quality glass waste (because of the contaminants associated with the glass waste and the variety of the color mixes).

Plastics Waste

According to Reinfield (1992) plastics are the second most valuable waste in community recycling. However, there are so many different types of plastics available in the market which are not easily identifiable even by many plastics experts. Therefore, the Plastic Bottle Institute has established a coding system dividing the most common plastic containers into seven major categories. This coding numbering system, which appears within a triangle shape on the bottom of each container, is to help recyclers and collectors of recycled materials to identify and separate them (Duston, 1993). The seven categories included in this coding system are as follows: 1 for polyethylene terephthalate, PET; 2 for high-density polyethylene, HDPE; 3 for polyvinyl chloride, PVC; 4 for low-density polyethylene, LDPE; 5 for polypropylene, PP; 6 for polystyrene or styrofoam, PS; and 7 for other, all other resins and multilayered materials. It is to be mentioned that within each of these categories there are many individual types of plastics (Carless. 1992). In general, the first two categories, PET (or often called two-liter soda bottles) and HDPE (milk jugs) are the most commonly recycled plastics while recycling the rest of the plastics is limited (Hegberg, Breuniman, & Hallenbeck, 1992). This is partially due to the time consumed, and high costs involved, in collecting and separating plastics according to their resins.

Unlike glass waste, plastics waste creates many serious problems. For example, plastics waste cannot be recycled to produce food-contact items due to the existence of contaminants even after recycling (Thorsheim, 1992). It also has another major problem which is its higher volume/weight ratio (i.e., plastics waste has lightweight which may occupy a large space in collection vehicle and in landfills as well) with respect to any other solid waste materials (U.S. Documents, 1991). An evidence for this higher volume/weight ratio is that plastics waste in the U.S. weighs about 8% of the total MSW in landfills while occupying over 20% of their total volume (Duston, 1993). On the other hand, the rate of plastics recycling is way below when compared to that of paper, aluminum, and glass. The EPA reported in the spring of 1990 that only about 1% of all plastics are recycled in the U.S.; mostly from PET and HDPE (Carless, 1992). It was also mentioned that the plastics industry uses five out of the six most polluting chemicals on an EPA list of chemicals whose production causes the most hazardous waste. These serious problems create a pressure on all parties (e.g. manufacturers, legislators, communities officials) involved with plastics waste to find feasible solutions.

One of the useful alternatives to overcome some of the problems associated with plastics waste is to combine plastics with other materials (plastics or others) to further increase its range of attributes. However, the high cost of producing these composites and the difficulty of recycling them while maintaining consistent quality products are the major obstacles for this area of industry. Currently, serious works are being conducted to overcome the numerous obstacles precluding further development of plastics recycling. These obstacles range from practical concerns (e.g. the lack of a well-developed infrastructure, low value/volume ratio, and high inventory costs) to environmental questions about the wisdom of recycling low cost petroleum-based products (Carless, 1992; Duston, 1993). Long life products (e.g. outdoor furnitures, plastic lumber, and polymer concrete) are optimum candidates to use plastics waste as part or whole of the constituents of these products (Hegberg et al., 1992; Shah, 1993).

Solid Waste-Construction Industry Relationship

The National Council on Public Works Improvement (1988) stressed, in its report to the president and the U.S. Congress, the critical need to improve two areas in the infrastructure: solid wastes and deteriorating highways. It is to be mentioned that negligence in confronting the problems associated with these two areas (e.g. the increase of solid waste materials in landfills with the reduction in the number of available landfills and the effect of deteriorating highways on the transportation of goods) immediately and swiftly may have strong negative effects on the economy of the nation. Rebeiz (1992) stated that, according to the Federal Highway Agency, more than 25% of the existing pavements in the U.S. are in deteriorating condition, and more than 40% of the 574,000 bridges in the U.S. are either structurally deficient or functionally obsolete. He mentioned that the estimated cost to rebuild the nation's roads is about $1.6 trillion.

As Carless mentioned (1992), the potential uses of most recyclables are almost endless. Many waste materials can be recycled either on a closed-loop or open-loop basis. This means that waste materials can go back to make either the same usable product (over and over again) or a new marketable one. One of the most promising markets to utilize recycled waste materials successfully on an open-loop basis is in the construction industry. Rebeiz (1992) stated three incentives to recycle solid waste materials in this industry:

1. Construction industry as the largest industry in the U.S. provides a huge potential market for recycled materials (especially plastics for repairing pavements and bridges).

2. Recycled materials (such as plastics) used in construction applications may not need to be as pure as those used in other applications. This simplifies the recycling process.

3. Construction products have estimated lives over 30 years which would provide for a long-term disposal of many waste materials (especially plastics waste). This is an important consideration in recycling operations.

Virgin and waste materials have been used in concrete composites since ancient times. Fibers such as straw and horse hair were used to reinforce brittle materials such as sunbaked bricks, masonry mortar and plaster. Later, large scale commercial use of asbestos fibers in a cement paste matrix began with the invention of Hatscheck process in 1900. However, partly due to the health hazards associated with asbestos fibers, different types and combinations of fibers (such as steel, glass, and plastics, sisal and jute) have been developed in the past 20-30 years (Shah, 1993).

Recently, many researchers have been working to incorporate virgin as well as solid waste materials with cementitious concrete mixtures to produce concrete composites having three main characteristics: (a) safety standards, such as compressive, flexural, impact, and splitting tensile strengths; (b) workability and durability; and (c) most importantly low production costs (Naville, 1981). Examples of such uses of different types of reinforcements in concrete materials can be found in the works of Fahmy et al., 1989; Magdamo, 1988; Rebeiz et al., 1991; Shah, 1993; Vaverka, 1991. Such fiber-reinforced concrete may be useful when a large amount of energy has to be absorbed and reduced cracking are desirable as well as when conventional reinforcement cannot be placed because of the shape of the member.

The idea of using waste materials as aggregate substitute is so new and very promising. Nasvik (1991) addressed the concept of using plastic aggregate as a colorful alternative to mineral aggregate. He stated many advantages of using plastic aggregates in concrete composite than that containing crushed limestone aggregate. Some of these advantages are higher compressive and flexural strengths, recycling plastic waste materials instead of disposing them, as well as more resistant to abrasion and impact. However, there are two major drawbacks of using plastic aggregates: cost production and the lack of in-field performance testing. A year later, Rebeiz (1992) stated that a portland cement concrete pedestrian bridge utilizing scrap plastic was constructed in Elgin, IL. The concrete bridge deck was composed of a mixture containing 30% granulated plastic as a partial replacement of sand. Although he mentioned that the main advantage of using plastic scrap in portland cement concrete is the reduction in dead weight with small loss of compressive strength, no further details have been revealed. Therefore, a thorough research study in the area of using different waste materials as aggregate substitute for cementitious concrete composites is needed.

Statement of The Problem

The problem of this research study was to investigate the possibility of using solid waste materials as granulated aggregate substitute in cementitious concrete composites. Specifically, the problem of this study was to determine the effect of substituting a certain percentage of the fine aggregate (sand, which is a finite natural resource) in the concrete mixture with one of the solid waste materials (glass, plastics, or fiberglass) on some of the mechanical properties (compression strength, splitting tensile strength, flexural strength, and flexural modulus of elasticity) as well as the interfacial bonding of the developed concrete composites.

Statement of The Purpose

The purpose of this study was to find an innovative method to produce a new cementitious concrete composite by using solid waste materials as aggregate substitute for the conventional portland cement concrete. The specific objectives of this research were:

1. To evaluate the possibility of using different granulated solid waste materials (plastics, glass, and fiberglass) from different sources as aggregate substitute to the natural fine aggregate (sand) in the portland cement concrete mixture to produce new cementitious concrete composites.

2. To characterize the following mechanical properties of the new concrete composites: compression, splitting tensile, flexural strengths as well as the flexural modulus of elasticity.

3. To compare the mechanical properties of the new developed concrete composites considering the types of waste materials used and their various volume percentages added to the portland cement concrete mixtures.

4. To determine the maximum percentage(s) by volume of solid waste materials used to produce new cementitious concrete composites.

5. To study the effect of using the maximum percentage(s) of solid waste materials added to the new concrete composites on their mechanical properties.

6. To use the Scanning Electron Microscope (SEM) to examine the interfacial bonding and microstructure of the new cementitious concrete composites.

Statement of Statistical Hypotheses

Table 1 shows the summary of the experimental variables that were involved in the present research study. Based on the mechanical properties (compressive, flexural, and splitting tensile strengths as well as flexural modulus of elasticity) of the cementitious concrete composites that were developed in this research study, the following research questions and research hypotheses were regarded:

Research Question 1

Is there any significant difference between the average values of the mechanical properties (compressive, flexural, and splitting tensile strengths as well as flexural modulus of elasticity) of the developed concrete composites using different volume percentages of plastics aggregate substitute (5, 10, 15, and 20%) added to these composites and those average values of the control concrete composites?

Research Hypothesis 1 (H_{11})

It is hypothesized that there will be a difference between the average values of the mechanical properties (compressive, flexural, and splitting tensile strengths as well as flexural modulus of elasticity) of the developed concrete composites using different percentages of plastics aggregate substitute (5, 10, 15, and 20%) added to these composites and those average values of the control concrete composites.

Null Hypothesis: H_0: $\mu_{Contr} = \mu_{P5}$
$= \mu_{P10}$
$= \mu_{P15}$
$= \mu_{P20}$

Table 1

Summary of the Experimental Variables Involved in the Present Research Study

Percentage of aggregate substitute	Type of aggregate substitute			
	Plastics specimens	Glass specimens	Fiberglass specimens	Experimental group mean
5%	$n = 5$ μ_{P5}	$n = 5$ μ_{G5}	$n = 5$ μ_{F5}	μ_5
10%	$n = 5$ μ_{P10}	$n = 5$ μ_{G10}	$n = 5$ μ_{F10}	μ_{10}
15%	$n = 5$ μ_{P15}	$n = 5$ μ_{G15}	$n = 5$ μ_{F15}	μ_{15}
20%	$n = 5$ μ_{P20}	$n = 5$ μ_{G20}	$n = 5$ μ_{F20}	μ_{20}
Experimental group mean	μ_5	μ_5	μ_5	

Research Question 2

Is there any significant difference between the average values of the mechanical properties (compressive, flexural, and splitting tensile strengths as well as flexural modulus of elasticity) of the developed concrete composites using different volume percentages of glass aggregate substitute (5, 10, 15, and 20%) added to these composites and those average values of the control concrete composites?

Research Hypothesis 2 (H_{12})

It is hypothesized that there will be a difference between the average values of the mechanical properties (compressive, flexural, and splitting tensile strengths as well as flexural modulus of elasticity) of the developed concrete composites using different percentages of glass aggregate substitute (5, 10, 15, and 20) added to these composites and those average values of the control concrete composites.

Null Hypothesis: H_0: $\mu_{Contr} = \mu_{G5}$
$= \mu_{G10}$
$= \mu_{G15}$
$= \mu_{G20}$

Research Question 3

Is there any significant difference between the average values of the mechanical properties (compressive, flexural, and splitting tensile strengths as well as flexural modulus of elasticity) of the developed concrete composites using different volume percentages of fiberglass aggregate substitute (5, 10, 15, and 20%) added to these composites and those average values of the control concrete composites?

Research Hypothesis 3 (H_{13})

It is hypothesized that there will be a difference between the average values of the mechanical properties (compressive, flexural, and splitting tensile strengths as well as flexural modulus of elasticity) of the developed concrete composites using different percentages of fiberglass aggregate substitute (5, 10, 15, and 20%) added to these composites and those average values of the control concrete composites.

Null Hypothesis: H_0: $\mu_{Contr} = \mu_{F5}$
$= \mu_{F10}$
$= \mu_{F15}$
$= \mu_{F20}$

Research Question 4

Is there any significant difference between the average values of the mechanical properties (compressive, flexural, and splitting tensile strengths as well as flexural modulus of elasticity) of the developed concrete composites using different percentages of plastics aggregate substitute (5, 10, 15, and 20%) added to these composites and those values of the new concrete composites using the same percentages of glass aggregate substitute?

Research Hypothesis 4 (H_{14})

It is hypothesized that there will be a difference between the average values of the compressive, splitting tensile, and flexural strengths as well as flexural modulus of elasticity of the developed concrete composites using 5, 10, 15, and 20% of plastics aggregate substitute added to these composites and those average values of the new concrete composites using the same percentages of glass aggregate substitute.

Null Hypothesis: H_0: $\mu_{P5} = \mu_{G5}$

$$\mu_{P10} = \mu_{G10}$$
$$\mu_{P15} = \mu_{G15}$$
$$\mu_{P20} = \mu_{G20}$$

Research Question 5

Is there any significant difference between the average values of the mechanical properties (compressive, flexural, and splitting tensile strengths as well as flexural modulus of elasticity) of the developed concrete composites using different percentages of plastics aggregate substitute (5, 10, 15, and 20%) added to these composites and those values of the new concrete composites using the same percentages of fiberglass aggregate substitute?

Research Hypothesis 5 (H_{15})

It is hypothesized that there will be a difference between the average values of the compressive, splitting tensile, and flexural strengths as well as flexural modulus of elasticity of the developed concrete composites using 5, 10, 15, and 20% of plastics aggregate substitute added to these composites and those average values of the new concrete composites using the same percentages of fiberglass aggregate substitute.

Null Hypothesis: H_0: $\mu_{P5} = \mu_{F5}$

$$\mu_{P10} = \mu_{F10}$$

$$\mu_{P15} = \mu_{F15}$$

$$\mu_{P20} = \mu_{F20}$$

Research Question 6

Is there any significant difference between the average values of the mechanical properties (compressive, flexural, and splitting tensile strengths as well as flexural modulus of elasticity) of the developed concrete composites using different percentages of glass aggregate substitute (5, 10, 15, and 20%) added to these composites and those values of the new concrete composites using the same percentages of fiberglass aggregate substitute?

Research Hypothesis 6 (H_{16})

It is hypothesized that there will be a difference between the average values of the compressive, splitting tensile, and flexural strengths as well as flexural modulus of elasticity of the developed concrete composites using 5, 10, 15, and 20% of glass aggregate substitute added to these composites and those average values of the new concrete composites using the same percentages of fiberglass aggregate substitute.

Null Hypothesis: H_0: $\mu_{G5} = \mu_{F5}$

$$\mu_{G10} = \mu_{F10}$$

$$\mu_{G15} = \mu_{F15}$$

$$\mu_{G20} = \mu_{F20}$$

Statement of Qualitative Hypotheses

The above six research questions and hypotheses were based on quantitative data obtained from the experimental part of this research study. However, the following research questions and hypotheses were based on the microstructure and the interfacial bonding between the aggregates and the cement paste of the concrete composites that were developed in this research study:

Research Question 7

Is there any observable difference between the microstructure and interfacial bonding of the developed concrete composites using various percentages of plastics aggregate substitute (5, 10, 15, and 20%) added to these composites and those microstructure and interfacial bonding of the control concrete composite?

Research Hypothesis 7 (H_{17})

It is hypothesized that there will be observable differences between the microstructure and interfacial bonding of the developed concrete composites using 5, 10, 15, and 20% of plastics aggregate substitute added to these composites and those of the control concrete composite.

Research Question 8

Is there any observable difference between the microstructure and interfacial bonding of the developed concrete composites using various percentages of glass aggregate substitute (5, 10, 15, and 20%) added to these composites and those microstructure and interfacial bonding of the control concrete composite?

Research Hypothesis 8 (H_{18})

It is hypothesized that there will be observable differences between the microstructure and interfacial bonding of the developed concrete composites using from 5 to 20% of glass aggregate substitute and those of the control concrete composite.

Research Question 9

Is there any observable difference between the microstructure and interfacial bonding of the developed concrete composites using various percentages of fiberglass aggregate substitute (5, 10, 15, and 20%) added to these composites and those microstructure and interfacial bonding of the control concrete composite?

Research Hypothesis 9 (H_{19})

It is hypothesized that there will be observable differences between the microstructure and interfacial bonding of the developed concrete composites using 5, 10, 15, and 20% of fiberglass aggregate substitute added to these composites and those of the control concrete composite.

Research Question 10

Is there any observable difference between the microstructure and the interfacial bonding of the developed concrete composites using from 5 to 20% plastics aggregate substitute added to these composites and those microstructure and the interfacial bonding of the new concrete composites using the same percentages of glass aggregate substitute?

Research Hypothesis 10 (H_{110})

It is hypothesized that there will be observable differences between the microstructure and interfacial bonding of the developed concrete composites using 5, 10, 15, and 20% of plastics aggregate substitute added to these composites and those microstructure and interfacial bonding of the new concrete composites using the same percentages of glass aggregate substitute.

Research Question 11

Is there any observable difference between the microstructure and the interfacial bonding of the developed concrete composites using different percentages of plastics aggregate substitute (5%, 10%, 15%, and 20%) added to these composites and those microstructure and the interfacial bonding of the new concrete composites using the same percentages of fiberglass aggregate substitute?

Research Hypothesis 11 (H_{111})

It is hypothesized that there will be observable differences between the microstructure and interfacial bonding of the developed concrete composites using 5, 10, 15, and 20% of plastics aggregate substitute added to these composites and those microstructure and interfacial bonding of the new concrete composites using the same percentages of fiberglass aggregate substitute.

Research Question 12

Is there any observable difference between the microstructure and interfacial bonding of the developed concrete composites using different percentages of glass aggregate substitute (5%, 10%, 15%, and 20%) added to these composites and those microstructure and interfacial bonding of the new concrete composites using the same percentages of fiberglass aggregate substitute?

Research Hypothesis 12 (H112)

It is hypothesized that there will be observable differences between the microstructure and interfacial bonding of the developed concrete composites using 5, 10, 15, and 20% of glass aggregate substitute added to these composites and those features of the new concrete composites using the same percentages of fiberglass aggregate substitute.

Assumptions

The following assumptions were made in pursuit of the present research study:

1. All the tested samples for the developed concrete composites were prepared and cured under the same laboratory working conditions.

2. All the waste materials used in this study (plastics, glass, and fiberglass) as aggregate substitutes in the cementitious concrete composites are representatives to their actual constituents as they exist in the solid waste stream. This assumption is enhanced by one of the findings of the research headed by William L. Rathje (1989) which states that all landfills basically have the same mix of wastes.

3. All the tested samples were identical as far as their preparation is concerned; i.e. the used aggregates and the cementitious concrete composites were mixed and then distributed in the tested samples homogeneously.

4. All the testing equipment used in this study were calibrated and controlled.

5. The basic concrete material which was used in this research study was a representative of actual materials in its class.

6. All the results obtained from the experimentation were only due to the existence of the granulated solid waste materials used as aggregate substitutes in the cementitious concrete composites. This means that other extraneous variables (such as water, cement, and gravel contents as well as experimental conditions) were controlled and did not have any influence on the results.

Limitations

The present research study was conducted in view of the following limitations:

1. Only one type of cementitious concrete mix design (Air-entrained portland cement concrete type IA) was used in this study as a cementitious concrete material.

2. All the tested samples were made and cured for 28 days before testing based on the specifications designated by the ASTM standard (1991a).

3. The dimensions of the tested cylindrical samples prepared for compression and splitting tensile tests were of 3" diameter x 6" height according to ASTM standards (1991b: 1991c) and Nasser and Kenyon (1984).

4. The dimensions of the tested beam samples prepared for flexural test were of 8" x 2" x 2" according to ASTM standard (1991d).

5. All results obtained and consequently all statistical treatment and evaluation were based on the above tested samples dimensions mentioned in 3 and 4 above.

6. Both plastics and glass waste materials used in the present study as aggregates were obtained from one source while fiberglass waste was obtained from another source.

7. All the solid waste materials used in this research study as aggregates were obtained in forms of granulated materials.

8. There were only three solid waste materials, out of all the materials that exist in the solid waste stream, involved in the present research study. These materials were plastics, glass, and fiberglass. Other solid waste materials such as paper, metals, rubber, etc. were not considered in this research study.

9. The plastics waste materials used in the present study were a combination of both the PET (soda bottles without metal caps and paper labels) and HDPE (milk jugs).

10. The glass waste materials used in the present study were a combination of both the clear glass window and fluorescent bulbs with a very small amount of contaminants.

11. The fiberglass waste materials used in the present study were a combination of unsaturated polyester base resin, styrene, continuous filament fiberglass, catalyst (Methyl Ethyl Ketone Peroxide), triethyl phosphate (TEP), gelcoats (styrene), and less than 0.5% contaminants (solem alumina trihydrate and calcium carbonate).

12. The present research study was only confined to investigating the effect of using three solid waste materials at four different volume fractions each (5, 10, 15, and 20%) on four of the mechanical properties of the cementitious concrete composites

(flexural, splitting tensile, and compressive strengths as well as flexural modulus of elasticity) and the microstructure and interfacial bonding of these composites.

Definitions of Terms

The following terms were defined to clarify their use in the context of the present research study:

Compressive Strength

Compressive strength is the measured maximum resistance of a tested specimen to axial compressive loading; expressed as force per unit cross-sectional area; or the specified resistance used in designed calculations (ACI Manual, 1992).

Fiberglass

In fiberglass types of composites, high-strength brittle glass fibers are embedded in a ductile matrix, having a fiber volume fraction of up to 40 percent. The resulted composites can be stronger and stiffer than the matrix and more ductile compared to the fiber behavior (Balaguru & Shah, 1992). Sometimes the term fiber glass has been used to indicate unsaturated polyester plastics. This term should refer only to fibrous pieces of glass. Various resins may be used with glass fiber acting as a reinforcing agent. The main use for unsaturated polyester is in the making of reinforced plastics while glass fiber is the most-used reinforcement (Richardson, 1989). Fiberglass is produced when molten glass, under steam pressure, is forced through very small holes. When cooled, it forms a network of thin glass fibers and air. The air acts as an insulator and therefore makes this an excellent material for insulating walls, ceilings, refrigerators, etc. (Pollack, 1988).

Flexural Strength

Flexural strength is the property of a material or a structural member that indicates its ability to resist failure in bending. In concrete flexural members, flexural strength is the bending moment at which a section reaches its maximum usable bending capacity. On the other hand, flexural strength for unreinforced concrete members is the bending moment at which the concrete tensile strength reaches the modulus of rupture (ACI Manual, 1992).

Municipal Solid Waste (MSW)

MSW refers to the overall garbage created by a community or entity. This means household waste as well as the waste created by the businesses, schools, and institutions in an area (Carless, 1992).

Normal Portland Cement (Type I)

It is the most widely used cement of the construction cements. It is a bluish-gray powder obtained by finely grinding the clinker made by strongly heating an intimate mixture of calcareous and argillaceous minerals. The chief raw material is a mixture of high-calcium limestone (known as cement rock) and clay or shale (Brady & Clauser, 1991). Type I portland cement is used in concrete that is not subject to aggressive exposures. Its uses in concrete include pavements, floors, reinforced concrete buildings, bridges, railway structures, tanks and reservoirs, pipe, masonry units, and other precast concrete products (Kosmatka & Panarese, 1988).

Plastics

The Society of Plastics Industry has defined plastics as follows:

> Any one of a large and varied group of materials consisting wholly or in part of combinations of carbon with oxygen, nitrogen, hydrogen, and other organic or inorganic elements which, while solid in finished state, at some stage in its manufacture is made liquid, and thus capable of being formed into various shapes, most usually through the application, either singly or together, of heat and pressure. (Richardson, 1989, p. 2)

To make plastics with different properties, a variety of ingredients such as stabilizers, colorants, or fillers are added. Plastics can be lightweight, unbreakable, flexible, and strong (Carless, 1992).

Recycling

Recycling is returning materials to their raw material components and then using these again to supplement or replace new (virgin) materials in the manufacture of a new product. In general, recycling also means simply putting something that was supposed to be thrown away into good use. The process of recycling usually involves the steps of separating materials from waste stream, collecting and processing them, and ultimately reusing either as entirely new product or as part of a new product (Carless, 1992).

Splitting Tensile Strength

It is the tensile strength of concrete determined by loading a cylindrical specimen to failure in diametral compression applied along the entire length (ACI Manual, 1992).

Workability of Fresh Concrete Mix

It is the ease with which a fresh concrete mix can be handled from the mixer to the final structure. The workability of fresh mixed concrete is the measure of how easy or difficult to place, consolidate, and finish this concrete (Somayaji, 1995).

Consistency of Concrete

The consistency of concrete is the ability of that freshly mixed concrete to flow. This measure of the concrete wetness or fluidity depends on the mix proportions and properties of the ingredients. It is generally measured with a slump test (Somayaji, 1995).

Plasticity of Concrete

The plasticity of concrete determines the concrete's ease of molding (Kosmatka & Panarese, 1988)

CHAPTER II

LITERATURE REVIEW

Introduction

Concrete has been the most widely used construction material in the past, is more useful today, and is expected to be indispensable tomorrow. It is generally used in many applications such as buildings, transit systems, and water and sewage-handling facilities. There are many reasons for the wide use of portland cement concrete in many applications:

1. Portland cement concrete has suitable engineering properties at relatively low cost. For example, concrete possesses excellent water resistance without serious deterioration. Therefore, concrete can be used to control, store, and transport water.

2. The production of concrete requires considerably less energy input compared to most other engineering materials.

3. The raw materials needed to produce concrete are relatively inexpensive and available in most areas of the world.

4. Portland cement concrete has ecological benefits.

5. Structural concrete elements can be easily formed into a variety of shapes and sizes due to the plastic consistency of the freshly made concrete which permits the material to flow into prefabricated formwork.

Researchers who work with cementitious concrete composites have to consider three main factors. The first factor is the complexity of the concrete structure and the difficulty of relating this structure to its properties. This is attributed to the fact that concrete contains a heterogeneous distribution of many solid components as well as pores of varying shapes and sizes which may be filled with alkaline solutions. The second factor is the dynamic property of the concrete structure due to the continuous change of both the bulk cement paste and the transition zone between the aggregate and this paste with time. And finally, concrete is unique since it is often manufactured just before use at or near the job site. Therefore, thorough understanding of concrete is most desirable to researchers and engineers than other construction materials. In the following sections available literature review about cementitious concrete composites is presented.

Cementitious Concrete Composites

A cementitious concrete composite is basically a mixture of inert filler materials (aggregates) and a cement paste. Aggregates, which make up about 60% to 80% of the total volume of concrete, are a mix of fine and coarse aggregates (Smith, 1993). Some of the aggregate characteristics which are significant to concrete technology include porosity, grading or size distribution, moisture absorption, shape and surface texture, crushing strength, elastic modulus, strength, hardness, and the type of deleterious substances present. The cement paste is composed of portland cement (the most common used hydraulic cement), water, and entrapped air or purposely entrained air. This paste plays a significant role in determining the quality of the concrete. It coats and binds the aggregates into a stonelike mass as the paste hardens due to hydration (a chemical reaction of cement and water). Since aggregate is cheaper than cement and has a higher volume stability and better durability than the cement paste alone, it is economical to put as much aggregate and as little cement as possible in the concrete mix (Neville, 1981). Each constituent of the cementitious concrete composite is described in more details in the following sections.

Fine Aggregates

Fine aggregates, to be used for concrete, consist of natural or manufactured sand with particle sizes ranging up to 3/8 inch. These aggregates should consist of clean, hard, durable, and uncoated particles. The particles should be free from organic matter, vegetable loam, alkali, or other deleterious substances that could affect the hydration and bonding processes of the cement paste. Stone screenings, slag, or other inert material may be substituted for or mixed with sand (Gamble, 1987). Sand for concrete should range in size from fine to coarse with consideration for the following conditions: the amount of sand that should pass a sieve No. 4 (4.75 mm) is 95% or more, 10% to 30% pass a sieve No. 50 (300 μm), and 2% to 10% pass a sieve No. 100 (150 μm) (ASTM, 1991h).

Size distribution of sand particles used in concrete structures should always be tested because of the influence of its quality on the strength, workability, and production cost of concretes. For example, very coarse sands produce harsh and unworkable concrete mixtures while very fine sands increase the water and cement requirement to secure the desired strength and are uneconomical. In practice, an empirical factor called the fineness modulus (FM) is often used as an index of the fineness of an aggregate. This index is computed from sieve analysis data by adding the cumulative percentages of aggregate retained on each of a specified series of sieves, and dividing the sum by 100. Kosmatka and Panarese (1988) stated that the fineness modulus must be between 2.3 and 3.1 and must not vary more than 0.2 from the typical value of the aggregate source. If this value is exceeded, the fine aggregate should be rejected unless suitable adjustments are made in proportions of fine and coarse aggregate.

The sieves used for determining the fineness modulus, according to ASTM standard (ASTM C136-84a, 1991) are: No. 100 (150 μm), No. 50 (300 μm), No. 30 (600 μm), No. 16 (1.18 mm), No. 8 (2.36 mm), No. 4 (4.75 mm), 3/8 inch (9.5 mm), 3/4 inch (19 mm), 1.5 inch (37.5 mm), 3 inch, and 6 inch. It may be noted that the higher the fineness modulus, the coarser the aggregate is. Following is an example listing sieve analysis and determination of fineness modulus of concrete sand in Table 2 and a typical grading curve (Figure 1) of how to determine the fineness modulus of fine aggregate for one of the concrete sand using ASTM C33 grading limits (Mehta, 1986).

Coarse Aggregates

Coarse aggregates used in concretes may consist of gravel, slag, or crushed stone particles (or other hard inert material with similar properties) retained on the No. 16 sieve (1.18 mm) and ranging up to 6 inch. Recycled concrete, or crushed waste concrete, is also a feasible source of coarse aggregates and an economic reality where good aggregates are scarce. The particles should be clean, hard, durable, and free from vegetable or organic matter, alkali, or other deleterious matter and should range in size from material retained on the No. 4 sieve to the coarsest size permissible for the structure (i.e. between 3/8" to 1.5").

Table 2

Sieve Analysis and Determination of Fineness Modulus of Concrete Sand

Concrete sand (456 g)		Sieve size								Total
		No. 4	No. 8	No. 16	No. 30	No. 50	No. 100	No. 200	Pan	
Weight retained		0.0	42.1	137.0	112.1	84.9	48.8	29.1	1.0	455.0
Retained %	Individual	0.0	9.2	30.2	24.7	18.7	10.8	6.4	0.2	F.M.
	Cumulative	0.0	9	39	64	83	94	100	100	2.89

Note. From "Concrete structure, properties, and materials" by P. K. Mehta. 1986.

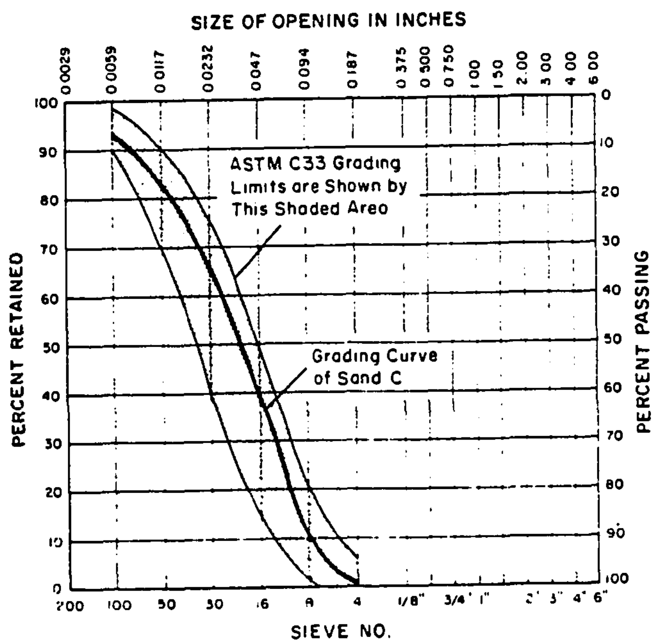


Figure 1. A typical grading curve of concrete sand sample.

Note. From "Concrete structure, properties, and materials" by P. K. Mehta. 1986.

For reinforced concrete and small masses of unreinforced concrete, the maximum size should be the one which will readily pass around the reinforcement and fill all parts of the forms (Gamble, 1987; Mehta, 1986).

It is recommended that lightweight fine aggregate not to be used in conjunction with lightweight coarse aggregate unless it can be demonstrated, from previous performance or suitable ASTM standard tests, that the particular combination of aggregates results in concrete that is free from soundness and durability problems. In case of doubt, the concrete mix should be designed using sand fine aggregate, and lightweight coarse aggregate. Their application is largely for concrete units and floor slabs where saving in weight is important and where special thermal insulation or acoustical properties are desired. It is to be mentioned that the volume of fine aggregate should not exceed 60% of that of coarse aggregate 1.5 inches maximum size or larger.

Kosmatka and Panarese (1988) stressed the importance of specifying grading and maximum aggregate size. These two factors can affect relative aggregate proportions as well as cement and water requirements, pumpability, porosity, shrinkage, and durability of concrete. It has been mentioned above that variations in grading can seriously affect the uniformity of concrete from batch to batch. Furthermore, aggregates of different maximum sizes may give slightly different concrete strengths for the same water-cement ratio. For example, concrete with smaller maximum-size aggregates may have higher compressive strength than that with larger maximum-size aggregates, at the same water-cement ratio. In general, aggregates that do not have a large deficiency or excess of any size and give a smooth grading curve will produce the most satisfactory results.

Some aggregate characteristics that a concrete mix designer should consider are the shape and surface texture of particles, specific gravity, and absorption and surface moisture. The shape and surface texture of an aggregate influence the properties of freshly mixed concrete more than that of hardened concrete. Smooth, rounded, and compact aggregates require less water to produce workable concrete than do rough-textured, angular, elongated ones. On the other hand, bonding between cement paste and rough and angular aggregates is generally stronger than that with smooth and rounded ones. This increase in bond should be considered when aggregates are selected for concrete with high compressive and flexural strengths (Mehta, 1986). The specific gravity of an aggregate is defined as the ratio of its weight to the weight of an equal absolute volume of water. It is used to calculate the absolute volume occupied by the aggregate in the design and control procedure of the concrete mix. ASTM C127 and C128 standard test methods are usually used to determine the specific gravity for coarse and fine aggregates. The absorption and surface moisture of aggregates are determined according to ASTM C70, C127, C128, and C566 so that the net water content in the concrete can be controlled and correct batch weights can be determined. Coarse and fine aggregates will generally have absorption levels (moisture content at saturated surface dry, where the concrete mixture neither absorbs water nor contributes) in the range of about 0.2 to 4% and 0.2 to 2% respectively. Free-water contents for coarse and fine aggregates will usually range from 0.5 to 2% and from 2 to 6% respectively (Kosmatka & Panarese, 1988).

Water

Water used in mixing concrete should be clean and free from oil, acid, alkali, organic matter, or other deleterious substances. Drinking water and many other types of non-drinking waters are normally satisfactory for concrete preparation. However, seawater used as a mixing water for plain concrete may lower the 28-day strength of this concrete than that for normal concrete. Also, if seawater is used in reinforced concrete, care must be taken to provide adequate cover with a dense air-entrained concrete to minimize risks of corrosion (Gamble, 1987).

In properly proportioned concrete, the unit water content required to produce a given slump (a measure for the workability and consistency of the concrete mixture) depends on several factors. As it has been mentioned above, water content increases as aggregates become more angular and rough textured and as the maximum size of well-graded aggregate decreases. However, mixing water content is usually reduced with the entrainment of air and by certain chemical water-reducing admixtures (ACI, 1992).

The amount of water used in relation to the amount of cement determines the quality of hardened concrete. Reducing water content in concrete increases the compressive and flexural strengths, resistance to weathering, and water tightness. It also improves the bonding between the successive layers and between concrete and reinforcement. Reducing water content in concrete also reduces the permeability and absorption, volume change from wetting and drying, and shrinkage cracking tendencies (Kosmatka & Panarese, 1988). It is to be noted that a very wet mixture (a mixture with an excess of water) of the same cement content is much weaker than a dry or mushy mixture. Mushy concrete is suitable as rubble concrete and reinforced concrete, for such applications as thin building walls, columns, floors, conduits, and tanks.

Cement

There are five types of portland cements covered by ASTM specification C150: Normal (type I), Modified (type II). High-early-strength (type III), Low-heat- (type IV), and Sulfate-resisting portland cements (type V). Type I portland cement is suitable for all uses where special properties of other types are not needed (e.g. pavements, floors, reinforced concrete buildings, bridges, and other precast concrete products). This cement is made from a mixture of about 80% carbonate of lime (limestone, chalk, or marl) and about 20% clay (in the form of clay, shale, or slag). After being intimately mixed, the materials are finely ground by a wet or dry process and then calcined in clinker. When cool, this clinker is ground to a fine powder. During the grinding, a small amount of gypsum is usually added to regulate the setting of the cement.

In addition to the above five types of portland cement, there are three types of air-entraining portland cement (Type IA, IIA, and IIIA) given in ASTM C150. These types correspond to Types I, II, and III, with the addition of small quantities of air-entraining materials mixed with the clinker during the manufacturing process. These cements improve the concrete resistance to freeze-thaw action and to scaling caused by chemicals and salts used for ice and snow removal. Such concrete contains microscopic air bubbles, separated, uniformly distributed, and so small that there are many billions in a cubic foot.

The strength of concrete increases with the increase of the quantity of cement in a unit volume relative to the quantity of mixing water. In addition, growth in strength with age primarily depends upon the consistency characteristics of the cement as well as the curing conditions. For example, if a cement is ground to finer particles, the heat of hydration will increase and consequently accelerating strength gain especially during the first 7 days. However, too fine cement may produce prehydration due to moisture vapor during manufacturing and storage, with the resulting loss in cementing properties of the material. Very coarse-ground cement particles may never completely hydrate (Herubin & Marotta, 1987).

It is to be mentioned that both flyash (resulted from the combustion of powdered coal in electrical power plants) and blast-furnace slag (resulted from the steel industry) may be used as either ingredients of blended cement or as separately batched materials. There are advantages in each method; the blended cement is convenient for storage while the batching (keeping the materials separate) allows different proportions to be used according to the needs of the project. Other advantages of using flyash and slag concrete include increased compressive and flexural strengths, decreased permeability and reduced shrinkage, reduced sulfate attack, reduced heat of hydration, reduced alkali/aggregate reaction, and thus increased durability (Plavsic, 1984).

Designing Concrete Mixtures

As it has been mentioned before, the main objectives in designing concrete mixtures are to determine the most economical and practical combination of the readily available materials to produce a satisfactory concrete to the performance requirements (e.g. intended use, size and shape of the required structures, exposure conditions, and physical and mechanical properties of the required structures). Once the mixture characteristics are selected, the mixture can be proportioned from field or laboratory data. There are two methods for estimating mix proportioning: weight method (which is fairly simple and quick for estimating mix proportions using an assumed or known weight of the concrete per unit volume) and absolute volume method (which is more accurate and involves the use of the specific gravity values for all the ingredients to calculate the absolute volume each will occupy in a unit volume of concrete. These two methods are described in the American Concrete Institute's Committee 211 standard practice for proportioning concrete mixes. The first step in proportioning a concrete mixture is the selection of the maximum aggregate size, air content, desired slump, and the lowest value of water-cement ratio that meets the durability, exposure, and strength requirements. Trial batches are then made varying the relative amounts of fine and coarse aggregate as well as other ingredients. Based on considerations of workability and economy, the proper mixture proportions are selected.

When a concrete mixture is to be designed, a specified compressive strength at 28 days (f'c) will generally be expected. Therefore, the average of any set of three consecutive strength tests should be at least equal to (f'c). According to ACI 318-83 (1986), no individual test (average of two cylinders) should be more than 500 psi below (f'c) when specimens are cured under laboratory conditions for individual class of concrete. Also the designer of concrete mix should add some allowances to (f'c) before calculating the amount of each constituent in the mix. These allowances are due to variations in materials and mixing methods, transporting, and placing the concrete, and testing concrete cylinder specimens. Therefore, the average strength (f'cr), which is greater than (f'c), is the strength required in the mix design. If the average strength of the mixtures with the statistical data is less than f'cr (or statistical data or test records are insufficient or not available), the mixture should be proportioned by the trial-mixture method. This means that three trial mixtures with three different water-cement ratios or cement contents should be tested. A water-cement ratio/strength curve can then be plotted and the proportions interpolated from the data. It is also a good practice to test the properties of the newly proportioned mixture in a trial batch (Kosmatka & Panarese, 1988).

Curing Concrete

The chemical reaction between the portland cement and mixed water is called hydration. This reaction should be completed to maintain the strength, durability, and density of the concrete. It is to be mentioned that any appreciable loss of water by evaporation (especially in the first few days where hydration is relatively rapid under room temperature) will delay or prevent complete hydration. This may cause the concrete to shrink and thus creating tensile stresses within it which result surface cracking. Therefore, it is important for the water to be retained in the freshly mixed concrete during this period and for evaporation to be prevented or at least reduced in order to obtain the desired properties. Curing does not only affect the strength, durability, and density of hardened concrete but also its water tightness, abrasion resistance, volume stability, and resistance to freezing and thawing, chemical attack, and deicer salts.

To prevent evaporation of water from the unhardened concrete specimens prepared in the laboratory, the finished specimens should immediately be covered. A nonabsorptive, nonreactive plate or sheets of tough, durable, impervious plastic are preferred to cover the outside surfaces of molded specimens and protect them from all contact with any source of water for the first 24 hours. This is because water may cause the molds to expand and damage specimens at this early age. Specimens removed from the molds should be moist cured (i.e. free water maintained on the entire surface area of the specimens) at room temperature until the time of test. Exposing the specimens to dripping or running water should be avoided at all times (ASTM C192, 1991).

The curing temperature can affect the strength of the hardened concrete drastically. If the concrete is cured for 3 to 7 days under low temperature than the standard, its 28-day compressive strength loss could be as much as 7%. Severe consequences can occur from actual freezing of the concrete. One day of freezing followed by standard curing can result in 28-day strength losses of as much as 56%. On the other hand, curing concrete under higher temperature than the standard for a week can reduce the strength as mush as 26% (Richardson, 1991). Richardson also stated that insufficient humidity during initial curing can lower measured strength. Air curing concrete for 3 to 7 days can lower strength by as much as 11% to 18% respectively.

As it has been mentioned above, the specified strength of concrete has been based traditionally on 28-day test results. However, in high-rise structures requiring high-strength concrete, the process of construction is such that the structural elements in lower floors are not fully loaded for periods of a year or more to ensure maximum strength. For this reason, compressive strengths based on 56- or 90-day test results are commonly specified to achieve significant economy in material costs (Kosmatka & Panarese, 1988).

Properties of Concrete

Concrete, which is basically a ceramic composite material, has a much higher compressive strength than tensile strength. Compressive strength is also the most universally used measure for concrete quality because it can be easily determined. It is frequently used in the design calculations for bridges, buildings, and other structures. Other mechanical properties, such as flexural and tensile strengths, can be empirically correlated to the compressive strength of the concrete mixture knowing the type of the material and the size of the member involved. However, some properties such as durability, permeability, and wear resistance may be equally or more important than compressive strength of concrete. The strength of concrete increases with the quantity of cement in a unit volume, with the decrease in the quantity of mixing water relative to cement content, and with the density of concrete. However, the strength of concrete is decreased by an excess of sand over that required to fill the voids in the stone and give sufficient workability. Other factors that influence the strength of concrete include the aggregate size, grading, surface texture, shape, strength, and stiffness; cement types and sources; entrained-air content; the presence of admixtures; and the length of curing time.

Strength tests of hardened concrete are usually performed on cylindrical samples with diameters of at least three times the maximum size of coarse aggregate in the concrete and of a length as close to twice the diameter as possible. Correction factors are available in ASTM C42 for samples with lengths of 1 to 2 times the diameter. Cylinders with a height of less than 95% of the diameter before or after capping should be discarded. Testing of specimens should be done in accordance with ASTM C39 (for compressive strength); ASTM C293 (for flexural strength using center-point loading); and ASTM C496 (for splitting tensile strength). It is to be mentioned that the amount of variation in compressive strength testing is far less than for flexural strength testing. Therefore, compressive strength tests can be used to monitor concrete quality if a laboratory-determined relationship has been developed between the compressive and flexural strength of the concrete used (Kosmatka, 1985).

Types of Concrete

Classification of Concrete Composites

In addition to the unlimited number of special types of concrete, there are three main groups used in classifying concretes: normal-weight, lightweight, and heavyweight concretes. Normal-weight concrete contains natural sand and gravel or crushed-rock aggregate and weighs between 130 to 155 pound per cubic foot (pcf). Lightweight concrete has a lower density and weight than that of normal-weight concrete. It uses certain natural or pyro-processed aggregates with lower bulk density and weighs between 85 to 115 pcf. Lightweight concrete usually has a 28-day compressive strength in excess of 2500 psi and is basically used to reduce the dead-load weight in concrete members such as floors in high-rise building. Heavyweight concrete is produced from high-density aggregates and weighs more than 200 pcf and up to about 400 pcf. These aggregates should be roughly cubical in shape (free of flat and elongated particles) and reasonably free of fine material, oil, and foreign substances that affect either the bond of paste to aggregate particle or the hydration of cement. Heavyweight concrete is used primarily for radiation shielding (especially if the available space is limited) and for other applications where high density is important (Kosmatka & Panarese, 1988; Mehta, 1986).

Some of The Special Types of Concrete Composites

Kosmatka and Panarese (1988) presented a long list for some types of special concretes. One of these types of concrete composites is the high-strength concrete which usually has a compressive strength of 6000 psi or greater. The production of this type of concrete often mandates the use of flyash or silica fume as an addition to the regular amount of cement, not as a partial substitute for it. This is because the strength gain obtained with these pozzolans cannot be attained by using additional cement alone. These pozzolanic materials are usually added at dosage rates of 5% to 20% by cement weight. Ground, blast-furnace slag can also be used in the production of high-strength concrete although its use for this purpose is small in the United States. Because of the high percentage of cementitious material in high-strength concrete, an increase in coarse-aggregate content beyond values recommended in standards for normal-strength mixtures is necessary and allowable. Also, the role of the fine aggregate (sand) in providing workability and good finishing characteristics is not as crucial as in conventional strength mixes. Coarse sand with a FM of about 3 has been found to be satisfactory for producing good workability and high compressive strength. Finer sand (with an FM of 2.5 to 2.7) may produce lower-strength and sticky mixtures.

Another type of special concrete composites demonstrated by Kosmatka and Panarese (1988) is porous concrete which is lightweight and has low shrinkage properties. It contains a narrowly graded coarse aggregate, little to no fine aggregate, and insufficient cement paste to fill voids in the coarse aggregate. This concrete, which can have as high volume of voids as 35%, is used in hydraulic structures as drainage media, and in parking lots, pavements, airport runways to reduce storm water run off, tennis courts, and greenhouses. It can also be used in building construction (particularly walls) for its thermal insulating properties (e.g., a 10-inch-thick porous-concrete wall can have an R value of 5 compared to 0.75 for normal concrete).

Fiber-Reinforced Concrete Composites

The use of randomly oriented, short fibers to improve the physical and mechanical properties (e.g. durability, ductility, and tensile strength) of a matrix is of a great interest to many researchers and engineering designers. These fiber/matrix composites could be natural fibers added to clay bricks or high-strength, fiber-reinforced ceramics components used in space shuttles. The matrices of concrete composites can consist of plain portland cement, cement with additives (such as fly ash, condensed silica fume, admixtures, or polymers), cement mortar containing cement and fine aggregate, or concrete containing cement, fine and coarse aggregates. The fibers of these concrete composites can be broadly classified as metallic fibers (steel or stainless steel), polymeric fibers (such as acrylic, aramid, nylon, polyester, polyethylene, and polypropylene fibers), mineral fibers (glass fiber is the predominantly used fiber), and naturally occurring fibers (such as cellulose, sisal, jute, coconut, abaca, bamboo, and flax and vegetable fibers). Fiber-reinforced concrete composite is being used for many applications such as bridges, pavements and industrial floors, tunnel and canal linings, hydraulic structures, pipes, explosion-resistant structures, safety vaults, cladding, and roller-compacted concrete.

In general, concrete mixtures using fibers contain a higher percentage of cement and fine aggregate as well as a smaller-sized coarse aggregate than plain concrete. Flyash may be added into the mixtures to offset the high cement content. The fibers vary in shapes (round, flat, crimped, and deformed) and sizes (lengths vary between 0.25 to 3 inches). Any designer who works with fiber-reinforced concrete should justify the use of fibers in concrete composites not only in terms of improving the properties of the composites but also in terms of cost. Since fibers are added to the concrete composites, additional cost must be considered. It is to be mentioned that the fiber content in the concrete composites should be carefully selected since high fiber contents produce unworkable concrete composites (although the mechanical properties of the composites will be improved) while low fiber contents do not show appreciable improvements in the properties of composites. Balaguru and Shah (1992) has categorized fiber-reinforced concretes into three groups:

1. Low fiber volume composites (less than 1% fiber) which is used for bulk applications involving large volumes of concrete containing coarse aggregate.

2. Moderate fiber volume composites (5 to 15% fiber) which is used for special applications such as safety vaults.

3. High fiber volume composites (more than 15% fiber) which is mainly used for thin sheets with either cement or cement mortar matrix.

In the beginning of modern-day use of fibers in concrete, only straight steel were used. The major improvement occurred in the areas of post-failure ductility and fracture toughness, as well as flexural strength and crack control (Edgington, Hannant, &

Williams, 1978). The primary factors that controlled the properties of the composite were fiber volume fraction (ranged from 150 to 200 lb/yd^3 of concrete) and length/diameter, or aspect, ratio of fibers (ranged from 60 to 100). The major problems encountered in the early stages were difficulty in mixing and workability especially at higher fiber volume fractions where the quality of the composite would be affected. The advent of deformed fibers (e.g. crimped, paddled, and enlarged ends) and high-range water-reducing admixtures eliminated the workability problem and aided the use of fibers in shotcrete. This admixture made it possible to proportion flowable mixes with low water-cement ratio. In recent applications, microsilica (silica fume which has lower permeability and higher strength) has often been used in shotcrete to make the mix cohesive, allowing workers to build greater thickness in a single pass (Balaguru & Shah, 1992).

The use of polymeric fibers in concrete has gained potential in the late 1970s. This was attributed to the low cost of plastics fibers related to other fiber materials such as steel and glass as well as to the improvement of the impact strength of concrete. However, polymeric fibers are now used in very low volume fraction (about 0.1% by volume), primarily to control cracking in the early stages of setting, typically less than three hours after casting. This application was developed using mainly polypropylene (PP) fibers due to its excellent chemical, physical, and mechanical properties compared to the reinforcement function and low cost. Naaman, Shah, and Throne (1984) found that the best bonding properties of PP fiber reinforced cementitious composites could be obtained by improving the mechanical bond of the fibers through adding end buttons to the fibers or by twisting them. Twisting was found to be superior due to the ease of achievement and the less time needed to produce. In 1987, Lovata and Fahmy (1987) investigated the effect of treating PP fibers chemically (by using a solution of a mild organic oleic acid and commercially prepared alkali solution of basic-H) on the compressive strength of PP fiber-reinforced concrete. The study revealed that these chemically treated PP fibers improved the strength of the concrete composites. Today, other polymeric fibers made of polyethylene, nylon, polyester, and cellulose are also being used. Krenchel and Shah (1985) stated that better understanding of the concepts behind fiber reinforcement, new methods of fabrication, and new types of organic fiber have led researchers to conclude that both natural and synthetic fibers can successfully reinforce concrete. However, Balaguru and Shah (1992) stressed the importance of using higher volume fractions than 0.1% in order to improve some properties of hardened concrete such as resistance to cracking caused by drying shrinkage.

The use of glass fibers in concrete was first attempted in the Soviet Union in the late 1950s. Since the ordinary glass fibers (including the borosilicate E glass fibers) are prone to attack by the alkaline environment of cement paste, later development was directed toward producing a form of alkali-resistant glass fibers (AR-glass) which is extensively used for architectural cladding. Glass fiber reinforced concrete (GFRC) can be made using different processes such as the spray-up process and a premix process. The primary concern in the development of GFRC is the durability of the glass fibers embedded in the highly alkaline concrete matrix. Balaguru and Shah (1992) stated that most of the research efforts are focused on the development of fiber and matrix compositions whose long-term durability and effectiveness are ensured.

A number of naturally occurring fibers are being investigated for manufacturing reinforced-cement sheets. Cellulose fibers seem to show promise for large-scale use. It has been used in the asbestos-cement industry to produce materials for indoor use. Other types include sisal, coconut, jute, abaca, and bamboo fibers have also been used in concrete composites. Magdamo (1988) discussed the use of many of these naturally occurring fibers in concrete composites fairly well. These natural occurring fibers may lack the durability required in the alkaline environment of concrete unless modifications are done either to the fiber surfaces or to the matrix composition.

The Use of Plastics Materials in The Construction Industry

The use of plastics is rapidly spreading in many industries (e.g., packaging, construction, automobile, aerospace). It also finds other cost-effective uses as a substitute for many traditional materials such as metals, glass, wood, paper, etc. The popularity of such wide applications is attributed to its lightweight, design flexibility, and manufacturing economy. Reisch (1994) stated that plastics used in building and construction are valued at about 7% of the $80 billion total for building and construction materials used annually in the U.S., according to New York City-based consulting firm Frost and Sullivan.

There are three polymeric concrete composites demonstrated by Naville (1981) and Plavsic (1984): polymer concrete (PC), polymer-impregnated concrete (PIC), and polymer portland cement concretes (PPCC). In PC, the aggregate is bonded by a synthetic resin (methyl methacrylate, epoxy, polyester-styrene, or even phenolics) instead of hydraulic cement. Depending on the materials used, PC can reach a compressive strength of as high as 20,000 psi within hours or even minutes. This advantage makes PC suitable for emergency concreting jobs in mines, tunnels, and highways. Despite the excellent chemical, physical and mechanical properties of the PC with respect to the conventional one, this type of composites is very expensive and may not be used except under very severe corrosion conditions. Another significant factor which influences the properties of the PC is its temperature dependency.

Polymer-impregnated concrete (PIC) is produced from conventional concrete made with portland cement, wet cured, and subsequently impregnated with a liquid or gaseous monomer and polymerized by gamma radiation or by chemically initiated means. The polymerized product has much higher compressive, tensile, flexure, and impact strengths than before treatment, a higher resistance to freezing and thawing, abrasion and to chemical attack. However, the main disadvantage of the PIC is its high production cost which limits its use to pipes carrying aggressive waters and in desalination plants. Polymer portland cement concretes (PPCC) is a premixed material in which either a monomer or polymer in a liquid, powdery, or dispersed phase is added to a fresh concrete mixture and then cured, and if needed polymerized in place. Polymer latexes used in this concrete improves durability, increases the workability of the fresh concrete and lowers the amount of water required compared with conventional concrete. PIC has excellent bond and impact strengths, freezing thaw and abrasion resistance, ease of application, and resistance to chlorides. It is widely used for overlays in industrial floors, and for rehabilitation of deteriorated bridge decks.

One of the most promising areas to utilize recycled plastics successfully is Polymer Concrete (PC) used in construction, rehabilitation, and maintenance of roads, and airfields. The effects of adding resin containing contaminated recycled polyethylene terephthalate (PET) on the mechanical properties of PC have also been reported in the literature (Rebeiz et al., 1991; Rebeiz et al., 1993). The percentage of the contaminated PET ranged from 15 to 40% of the used resin. The designed mixture revealed improvement in many properties such as creep, flexural strength, young's modulus, compression and bonding stresses, shrinkage, and thermal expansion. These results were comparable to those of virgin resin. PC with lower costs compared to portland cement concrete is being preferred in many applications. Still further reduction in the cost of the PC would be more appealing to the designers and constructors. If recycled commingled plastics waste can be used to produce PC with required properties, it could reduce the plastics solid waste dramatically, and also the production cost.

Aggregates From Recycled Concrete and Waste Materials

Rubble from demolished concrete buildings yields fragments in which the aggregate is contaminated with hydrated cement paste, gypsum, and other substances. The size fraction which corresponds to fine aggregate and contains mostly hydrated cement paste and gypsum is not suitable for making fresh concrete mixtures. However, the size fraction that corresponds to coarse aggregate, although coated with cement paste, has been used in several laboratory and field studies. Compared with concrete containing a natural aggregate, the recycled-aggregate concrete would have at least 2/3 of the compressive strength and modulus of elasticity, and satisfactory workability and durability. Obstacles for widespread use of rubble are the cost of crushing, grading, dust control, and separation of undesirable constituents. Recycled concrete or waste concrete that has been crushed can be an economically feasible source of aggregate where good aggregates are scarce and when the cost of disposal is included in the economic analysis (Mehta, 1986).

Investigations have also been made to evaluate municipal wastes and incinerator residues as possible sources for concrete aggregates. Glass, metals, paper and organic materials are major constituents of MSW. Mehta (1986) stated many disadvantages of using these waste material in concrete composites. He claims that the presence of crushed glass in aggregate tends to produce unworkable concrete mixtures and, due to the high alkali content, affects the long-term durability and strength. Metals such as aluminum react with alkaline solutions and cause excessive expansion. Paper and organic wastes, with or without incineration, cause setting and hardening problems in portland cement concrete. He has concluded that, in general, municipal wastes are not suitable for making aggregates for use in structural concrete.

However, the possibility of using different types of waste vegetable materials of low bulk densities in concrete composites has been investigated by many researchers and institutes. For example, the Tropical Products Institute in India investigated the use of rice husk as a concrete aggregate. Results showed the possibility of using this material in concrete very effectively (Cook, 1980). Rebeiz (1992) stated also that a portland cement concrete pedestrian bridge utilizing scrap plastic was constructed in Elgin, IL. The concrete bridge deck was composed of a mixture containing 30% granulated plastic as a partial replacement of sand. Although he mentioned that the main advantage of using plastic scrap in portland cement concrete is the reduction in dead weight with small loss of compressive strength, no further details have been revealed. Therefore, further studies are needed to investigate the possibility of using solid waste materials as a partial substitute of sand for new developed concrete composites. Three main objectives must be met when new developed concrete composite is to be produced: (a) the fresh mixed concrete has acceptable workability, consistency, and plasticity suitable for the job conditions; (b) the hardened concrete is durable, meets strength requirement, and has a uniform appearance; and (c) the developed concrete composite is economically justified. The current research study is an effort to produce these types of cementitious concrete composites.

CHAPTER III

RESEARCH METHODOLOGY

Introduction

Any designer who works with concrete mixtures should be aware of three main factors. The first factor is to make sure that the fresh mixed concrete has acceptable workability, consistency, and plasticity suitable for the job conditions. Secondly, the hardened concrete should be durable, meet the strength requirement, and has a uniform appearance. Thirdly, the designer should consider the economic factors of the designed concrete mixture (Mehta, 1986). Failure in considering these factors may affect the versatility and the usefulness of the concrete mixtures.

Thorough understanding of the basic principles of the design of concrete mixtures is of the same importance as the actual design calculations. This simply means that the designer should not only select the proper materials and mixture characteristics but also select the proper proportioning of these materials that fulfill the three factors mentioned above in the scope of the intended application(s). The task of designing new developed concrete mixtures may add more complexity to the designer's job since no previous data are available to help in starting the design procedure. In this case, the mixture should be proportioned by the trial-mixture method until satisfactory mixture is obtained as has been mentioned earlier in chapter II.

In this chapter, the fundamentals of the experimental design of the present research study is described in detail. Since the proposed developed concrete composites are new in nature (due to the fact that the waste materials will be used as fine aggregate substitute), a step-by-step procedure for preparing the tested samples is presented. An overview of the three tests used to determine some of the mechanical properties for the different types of the developed cementitious concrete composites is also described in detail. Statistical analysis and representation of the obtained experimental data as well as the proposed microscopic study of the interfacial bonding and microstructure of the tested specimens using scanning electron microscopy (SEM) are discussed.

Experimental Design

The present research study concentrated on using three different waste materials (plastics, glass, and fiberglass) added individually as aggregate substitutes for a portion of the fine aggregate (sand) of the cementitious concrete composites. Four different volume percentages (5, 10, 15, and 20%) of each material were used to produce different cementitious concrete composites. For each developed concrete composite, five to six identical specimens were tested to determine each of the four mechanical properties of that composite. For example, five or six identical specimens of the 5% of plastics (which replaced 5% of the total volume of the fine aggregate content in the concrete mixture) were used for each one of the proposed test methods to characterize the mechanical properties of this composite at that percentage. Three other sets of the five/six identical specimens for the other proposed percentages of plastics (10, 15, and 20%) were also tested. Table 3 shows the mechanical testing planned, and the number of tested specimens conducted in this study. Also, the following section outlines the conceptual scheme of how the experimental design was conducted to substitute a portion of the volume of the sand with one of the three granulated waste materials.

Calculation Method

The following steps were considered during the preparation of the specimens of the controlled group and those of the experimental groups:

For the Specimens of the Control Group

1. According to the ACI standard (1992), the required water content and recommended air content for the required slump and maximum size of aggregate available were found:

The required weight of water content per cubic yard = W_W lb/yd^3 (1)

2. According to the ACI standard (1992), it was assumed that for the required compressive strength and characteristic of the concrete (air-entrained concrete) that:

The water-cement ratio = r_{WC}

Then, The required cement content (W_C) = W_W / r_{WC} lb/yd^3 (2)

Table 3

Mechanical Testing Method and Number of Tested Specimens

Aggregate substitute and percentages		Mechanical testing and number of tested specimens			Total number of specimens
		Compression test	Flexural test	Splitting tensile test	
Control specimens		5	5	6	16
Plastics specimens	5%	5	5	6	64
	10%	5	5	6	
	15%	5	5	6	
	20%	5	5	6	
Glass specimens	5%	5	5	6	64
	10%	5	5	6	
	15%	5	5	6	
	20%	5	5	6	
Fiberglass specimens	5%	5	5	6	64
	10%	5	5	6	
	15%	5	5	6	
	20%	5	5	6	
Total number of specimens		65	65	78	208

3. According to the ACI standard (1992), it was assumed for the available maximum size of aggregate, fineness modulus of the fine aggregate available, and ovandry rodded unit weight of coarse aggregate per cubic foot that:

$$\text{The required coarse aggregate content} = W_{CA} \quad \text{lb/yd}^3 \qquad (3)$$

4. From steps 1, 2, and 3, the volumes of the water, cement, coarse aggregate, and entrapped air were determined per cubic yard:

$$\text{Volume of water } (V_W) = W_W / (\rho_W \times \gamma_W) \quad \text{ft}^3 \qquad (4)$$

$$\text{Volume of cement } (V_C) = W_C / (\rho_W \times \gamma_C) \quad \text{ft}^3 \qquad (5)$$

$$\text{Volume of coarse aggregate } (V_{CA}) = W_{CA} / (\rho_W \times \gamma_{CA}) \quad ft^3 \qquad (6)$$

$$\text{Volume of entrapped air } (V_A) = P_A \cdot (27) \quad ft^3 \qquad (7)$$

Where:

ρ_W = Density of water = 62.4 (lb/yd^3) / ft^3

γ_W = Specific gravity of water = 1

γ_C = Specific gravity of cement

γ_{CA} = Specific gravity of coarse aggregate

5. From equations 4 through 7, the volume of the fine aggregate (sand) per cubic yard was also determined:

$$\text{Volume of fine aggregate } (V_{FA}) = 27 - (V_W + V_C + V_{CA} + V_A) \quad ft^3 \qquad (8)$$

6. From step 5, the following was determined:

$$\text{The required Fine Aggregate content } (W_{FA}) = V_{FA} \cdot (\rho_W \times \gamma_{FA}) \quad lb/yd^3 \qquad (9)$$

<u>For the Specimens of the Experimental Groups</u>

Steps 1 through 4 mentioned above were the same. After determining the volume of fine aggregate from step 5, as shown above, a portion of this volume (p) was substituted by one of the waste materials (plastics, fiberglass, or glass). Hence, the required fine aggregate content (W_{FA1}) was calculated as follows:

$$W_{FA1} = (1-p)\, V_{FA} \cdot (\rho_W \cdot \gamma_{FA}) \quad lb/yd^3 \qquad (10)$$

From the volume of the waste material determined from step equation (10) and the specific gravity of that material, the required waste material content (W_{WM}) was found as follows:

$$W_{WM} = (p)\, V_{FA} \cdot (\rho_W \cdot \gamma_{WM}) \quad lb/yd^3 \qquad (11)$$

In order to accomplish the experimental design mentioned above successfully, few steps were completed. First, after receiving the waste materials from the suppliers the contents of these materials and some of their physical properties (e.g. specific gravity and grain size distribution), as well as those properties of the aggregates and portland cement, were determined. Then, detailed procedure to calculate the proportions of the constituents of each developed concrete mixture was conducted as outlined above. Preparation of all the laboratory specimens for the proposed mechanical tests were in accordance with the standard practices and methods (ASTM standards 1991b, 1991c, and 1991d). Figure 2 shows a conceptual schematic of how the experimental design was conducted to substitute a portion of the volume of the fine aggregate (sand) with one of the three granulated waste materials. After making and curing these specimens (in accordance with ASTM standard 1991a) for 28 days, three different test methods were conducted to determine four mechanical properties of the developed concrete composites. These properties are the compressive strength, splitting tensile strength, modulus of elasticity, and flexure strength. Statistical analysis of the obtained results for the different concrete composites was to follow, to compare these composites with each other in the scope of the research questions mentioned in chapter I. Finally, a study was conducted by using the scanning electron microscope (SEM) to show the characteristics of each of the developed cementitious concrete composites in terms of the interfacial bonding between the aggregate and the cementitious paste. Also, the general fracture behavior of the developed concrete composites was studied through visual analysis of generated photographs of these specimens after testing was completed.

Sample Preparation

In order to prepare the test samples for the three intended tests, the ASTM standards were followed to determine the physical properties of the ingredients of the cementitious concrete composites (e.g. the specific gravity and water absorption). These properties were essential for accurate design calculations for the new concrete composites. The following was the procedure of how to prepare the specimens which were used in the present research study:

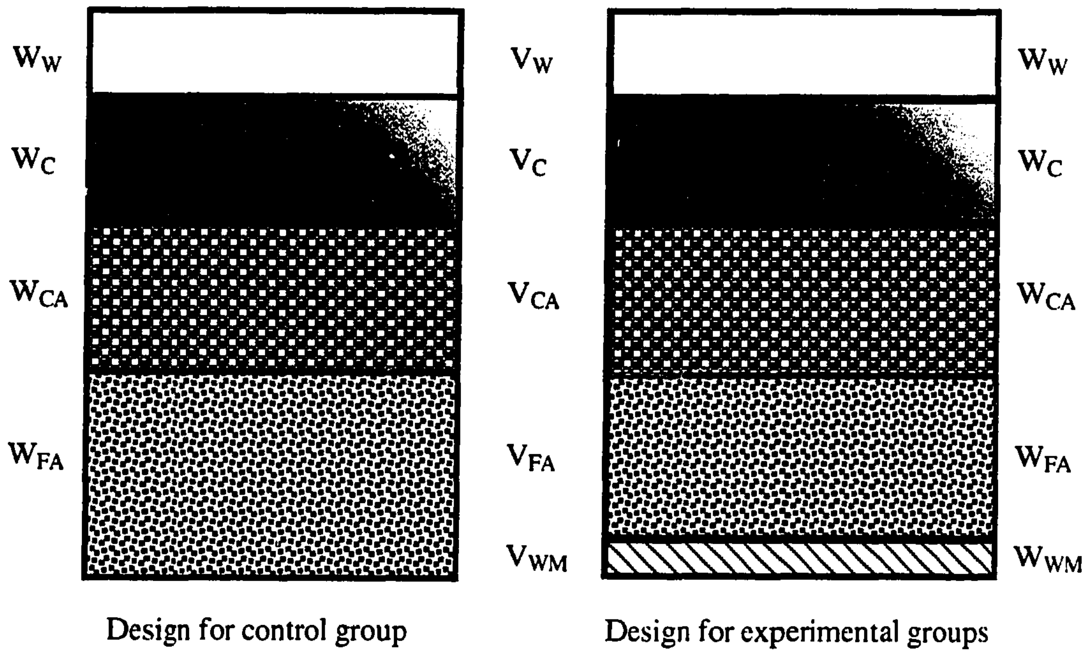


Figure 2. A conceptual scheme of the conducted experimental design.

1. Determining the specific gravity and absorption of coarse aggregate (gravel) in accordance with ASTM standard (1991e).

2. Determining the specific gravity and absorption of fine aggregate (sand) in accordance with ASTM standard (1991f).

3. Determining the specific gravity of plastics in accordance with ASTM standard (1991g).

4. Determining the specific gravity of glass and fiberglass in accordance with ASTM standard (1988).

5. Determining the sieve analysis of fine aggregate (sand) and its substitutes (plastics, glass, and fiberglass) in accordance with ASTM standard (1991h).

6. Calculating the proportions of the ingredients of the concrete mixtures used to prepare the number of tested specimens for each test case in accordance with ACI manual of concrete practice (1992).

7. Performing the developed concrete test specimens in the laboratory in accordance with ASTM standard (1991a).

8. Measuring the slump of the specimens of the experimental groups (new cementitious concrete composites) as well as the specimens of the control group in accordance with ASTM standard (1991i).

9. Curing the developed concrete test specimens in the laboratory in accordance with ASTM standard (1991a).

It is to be noted here that Type IA normal Portland cement (air-entraining) concrete was the bases for the preparation of all the test specimens that were used in this study.

Samples Configurations

Generally, there are three types of compression test specimens used: cylinders, cubes, and prisms. Cylinders are the standard specimens in the United States according to ASTM (1991b). These cylindrical specimens are preferred nowadays over the other two standard specimens especially in research (Neville, 1981). In the current research study, the standard cylinders (which is used in both compressive and splitting tensile tests) were prepared in accordance with ASTM standard (1991a). Figure 3 shows the geometry of the standard cylinders used in these two tests. The dimensions of these cylinders were 3 x 6 inches. since the available maximum size of aggregate did not exceed one in. according to Nasser and Kenyon (1984). On the other hand, the standard specimens for the flexural test were of rectangular beam shape as shown in Figure 4. The dimensions of these specimens were in accordance with ASTM standard (1991d).

Testing Methods

Three mechanical testing methods were conducted in the present research study to calculate four properties of the developed cementitious concrete composites: compressive, splitting tensile, and flexural strengths as well as modulus of elasticity. All these tests were in accordance with the ASTM standards (1991b, 1991c, and 1991d respectively). The following is detailed information about each of the three testing methods:

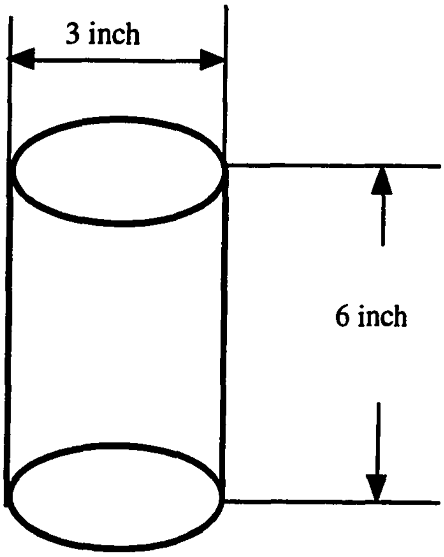


Figure 3. Specimen configuration for both compression and splitting tensile tests.

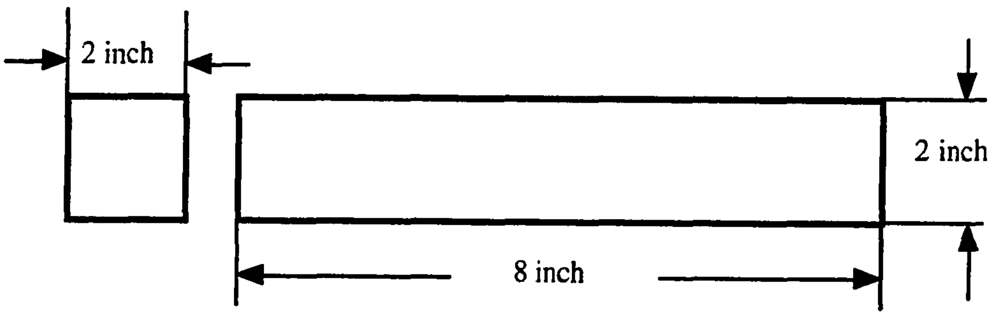


Figure 4. Specimen configuration for flexural test.

Compression Test

Compressive strength of concrete is a primary mechanical property and usually used in the design calculations for such applications as pavements, bridges, buildings, and other structures. It can be defined as the maximum resistance of concrete mixture to axial loading and generally expressed in pounds per square inch (psi) at an age of 28 days (curing period). This is because many normal portland cements today show very little gain in strength after 28 days (Gamble, 1987). Most general-use concrete composites have a compressive strength between 3000 psi and 5000 psi. High-strength concrete has a compressive strength of at least 6000 psi and this value can reach 20,000 psi for building structures (Kosmatka & Panarese, 1988).

The testing method used to determine the values of compressive strength for the experimental groups (the new cementitious concrete composites) as well as for the control group (controlled specimens) were based on the ASTM C39-86 standard (1991b). All the tested specimens were capped (using standard capping compound) from both surfaces of each specimen to ensure flat surfaces where the applied load was perpendicular to these surfaces. The values of the compressive strength were obtained by applying a compressive axial load to molded concrete cylinders (3" of diameter by 6" of length) at a rate which was within a prescribed range (20 to 50 psi/s or about 140 to 350 lbs/s) until failure occurs. The compressive strength (f'_c) of each of the test specimens was calculated as follows:

$$f'_c = P / A \qquad (12)$$

Where: f'_c = Compressive strength (psi)

P = Maximum applied load (lb)

A = Cross-sectional area of the specimen (in^2)

Splitting Tensile Test

The splitting tensile strength is another measure used to evaluate the shear resistance provided by concrete composites in reinforced lightweight aggregate concrete members. This measure is simpler to determine than direct tensile strength. The testing method used to determine the values of splitting tensile strength for the experimental groups (the new cementitious concrete composites) and the control group (controlled specimens) was based on the ASTM (C496-90) standard (1991c). This value was obtained by applying a continuous diametral compressive force at a constant rate (100 to 200 psi/min or about 2850 to 5700 lbs/min) to a cylindrical concrete specimen (3" of diameter by 6" of length). The specimen was placed with its axis horizontal between the bearing blocks of the testing machine. Additional apparatus was used to align the concrete specimens directly beneath the center of the thrust of the spherical bearing block and to ensure uniformly distributed load along the length of each specimen. The apparatus included a supplementary bearing bar (a tempered steel bar measuring 1 square inch by 7 inches long) and two bearing strips (plywood strips of 1/8 inch thick x 1 inch wide x 7 inches long). The maximum applied load indicated by the testing machine at failure was recorded. Then, the splitting tensile strength ($\underline{T}$) was computed as follows (Avallone & Baumeister, 1987):

$$\underline{T} = 2\,P / (\pi\, l\, d) \qquad (13)$$

Where: $\underline{T}$ = Splitting tensile strength (psi)

P = Maximum applied load (lb)

l = The length of the cylinder (in)

d = The diameter of the cylinder (in)

Flexural Test

Flexural strength and modulus of elasticity of concrete is generally used in designing pavements and other slabs on ground. The test specimens, as well as the testing procedure, were in conformance to all requirements of ASTM C293-79 standard (1991d). The geometry and loading configuration of the tested specimens are shown in Figure 5. The test specimen was loaded continuously and without shock at a constant rate (125 to 175 psi/min or about 110 to 160 lbs/min) until rupture occurs. It is to be mentioned here, that an X-Y recorder was used to generate the load-deflection curve for the tested specimen. Also, the testing machine had the capability to read the maximum applied load and the maximum deflection. These values and the dimensions of the specimen were recorded.

These values were used to calculate both the modulus of rupture (R) and the flexural modulus of elasticity (E):

$$\underline{R} = (3\,P\,l) / (2\,b\,d^2) \qquad (14)$$

$$\underline{E} = (P\,l^3) / (4\,\delta\,b\,d^3) \qquad (15)$$

Where: $\underline{R}$ = Modulus of rupture (psi)

$\underline{E}$ = Flexural modulus of elasticity (psi)

P = Maximum applied load (lb)

l = Span length of the beam (in)

b = Average width of specimen, at the point of fracture (in)

d = Average depth of specimen, at the point of fracture (in)

δ = Maximum deflection at the center point of the specimen at fracture (in)

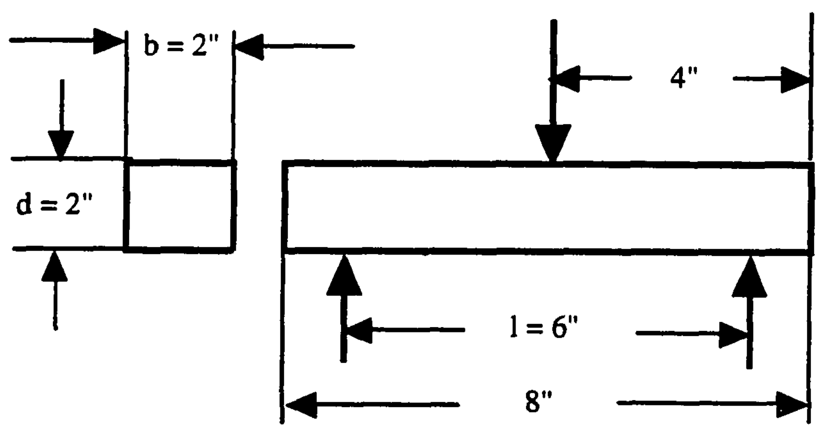


Figure 5. Specimen geometry and loading configuration for flexural test

Laboratory Equipment

All specimens for the developed cementitious concrete composites were prepared and tested using equipment available in the Production and Material Testing laboratories in the Department of Industrial Technology, University of Northern Iowa (UNI). All molds needed to prepare standard specimens for the three conducted tests were in accordance with

ASTM (C39-86, C496-90, C293-79) standards (1991b, 1991c, and 1991d respectively). The compression and splitting tensile tests were conducted by using the hydraulic SoilTest Versa-Tester (Model 30-K machine) with a maximum applied force of 60,000 lb. On the other hand, an ATS (applied test system) with a maximum force of 5000 lb., Series 900 UTM (universal test machine) with an X-Y recorder was used in conducting the flexural test. Both of these machines were standardized and calibrated to obtain accurate and representative data for the actual behavior of all the new cementitious concrete composites.

Statistical and Microscopic Analyses

All the results obtained from the experimental part of the current research study were used in the statistical analysis part. According to the research questions stated in chapter 1, there were two types of analysis that were used in comparing and discussing the observed and recorded data. For the quantitative results (Research Questions 1 through 6), a two-way factor using the percentage and type of aggregate substitute as a two-way analysis of variance (Two-Way ANOVA) method was used. One-Way ANOVA method and an appropriate post hoc test such as Tukey's test were also used. The structure of the problem can be seen in Table 1 (Chapter 1). Graphical representation for the obtained results are included to compare the developed cementitious concrete composites.

On the other hand, the part concerning the use of the scanning electron microscope (SEM) to study the microstructure and interfacial bonding of the new concrete composites (Questions 7 through 12) is described through the visual analysis of the SEM micrographs of the microstructures and interfacial bonding between the aggregates and concrete paste. It is to be mentioned that a Hitachi S-570 SEM available at UNI was used in the microscopic study part of the current study. Also, the general fracture behavior of the new concrete composites is studied through visual analysis of the generated photographs.

CHAPTER IV

EXPERIMENTAL RESULTS AND DISCUSSION

Introduction

The purpose of this research study was to evaluate the possibility of using different granulated solid waste materials (plastics, fiberglass, and glass) as partial aggregate substitutes to the fine aggregate (sand) in a portland cement concrete mixture to produce new concrete composites. Therefore, three different test methods were conducted to study such mechanical properties as compressive and splitting tensile strengths, modulus of rupture, and flexural modulus of elasticity of the new concrete composites. In addition, a scanning electron microscope (SEM) was used to study the microstructure and interfacial bonding of the developed concrete composites. Optical photographs were also taken to show the general fracture behaviors of the developed concrete composites after failure. It is anticipated that this study will determine the maximum percentage(s) by volume of solid waste materials that can be used to produce new cementitious concrete composites while maintaining good mechanical properties. Of course, this type of research study also aims to reduce the solid waste materials disposed in landfill and the reuse of some of these materials in the construction industry which is one of the most promising markets worldwide.

In this chapter, the results of the experimental part of the present research study are presented. Data (e.g. specific gravity of different materials and water absorption of sand and gravel) needed to design control and experimental groups is given and discussed. Complete lists of parameters associated with the three tests used to determine the mechanical properties for the different types of the new cementitious concrete composites are also presented and described in more details. Statistical analysis and representation of experimental data (tables and graphs) are demonstrated. Finally, a comprehensive study is conducted to correlate the mechanical properties of the new cementitious concrete composites and their general fracture behaviors (using optical photographs) and their interfacial bonding and microstructures (through micrographs generated by using scanning electron microscopy, SEM).

Preparation Data of the Cementitious Concrete Composites

The present research study was basically concentrated on using three different waste materials (plastics, glass, and fiberglass) individually as aggregate substitutes for a portion of the fine aggregate (sand) of the cementitious concrete composites. Therefore, the properties of these materials as well as of water, cement, and coarse aggregate were necessary to design both control and experimental groups according to ACI standard (1992). Firstly, drinking water at room temperature (about 73°F) was used to prepare all tested samples. Secondly, Type IA normal Portland cement (air-entraining) concrete was the basis for the preparation of all the test specimens that were used in this study. The specific gravity of this cement (γ_C) was 3.15.

It is to be mentioned here that the recommended slump range considered in the current research study was between 1 and 3 inches according to the ACI standard (1992). This value was chosen to accommodate many fields of concrete construction industries such as reinforced foundation walls and footings; plain footings, caissons, and substructure walls; and pavements and slabs. This value of slump as well as the shape and maximum sizes of coarse aggregates (which were smooth and round gravels with an average diameter of 3/8" for the present research), type of concrete, and exposure conditions determined the amount of water and air content needed for the trail batch of the controlled concrete group (which was modified to prepare the experimental groups).

Due to the fact that no previous data were available to establish a standard deviation for the average compressive strength of the new cementitious concrete composites, some allowances to the specified 28-day compressive strength (f'_c = 3000 psi for the present research study in accordance with the ACI standard,1992) was added before calculating the amount of each constituent in the concrete mix. Therefore, the average strength required (f'_{cr} = 4200 psi) was considered in the mix design. This value and the type of concrete were the basis to determine the water/cement ratio and the amount of cement needed for the trail batch of the controlled concrete group.

In order to find the desired amount of coarse aggregate needed for the trial batch, few steps were performed. The oven dry rodded unit weight of coarse aggregate was calculated (101 lb/ft^3). Then, the maximum size of coarse aggregate was determined to be 3/8 inch as well as the fineness modulus (FM = 2.7) of the fine aggregate through the sieve analysis of aggregates and in accordance with ASTM standard (1991h). The volume of dry-rodded coarse aggregate per unit volume of concrete was then calculated by knowing the maximum size of coarse aggregate and fineness modulus of the fine aggregate and in accordance with the ACI standard (1992). Finally, the amount of coarse aggregate was calculated by knowing the volume of dry-rodded coarse aggregate per unit volume of concrete and the ovendry rodded unit weight of coarse aggregate.

After calculating the amounts of water, cement, and coarse aggregate (dry) in the trial batch of the concrete mix design, the volume contents of these ingredients and the entrapped air, were determined in accordance with ACI standard (1992). This is simply because using concrete mix designs by volume method is more accurate than the weight method. The density of water as well as the specific gravity of the water, cement, and coarse aggregate needed to find the volume contents of these materials were 62.4 (lb/yd^3) / ft^3, 1, 3.15 and 2.64 respectively. These values of volume contents of water, cement, coarse aggregate, and entrapped air were used to find the volume content of the fine aggregate. Consequently, the amount of fine aggregate (dry) needed in the trial batch of the concrete mixture was calculated using its volume content and specific gravity (which was equal to 2.7 based on ASTM standard, 1991f).

In order to complete the design of the trial batch, corrections were made to compensate for moisture existed in both the fine and coarse aggregates. Therefore, the absorption (moisture content at saturated surface dry, SSD, condition) and laboratory sample moisture content of the coarse and fine aggregates were determined in accordance with ASTM standards (1991e; 1991f). These values were 0.31% and 0.51% for the coarse aggregate and 1.01% and 4.85% for the fine aggregate respectively. These values were used to determine the wet amounts of the coarse and fine aggregate (which will be greater than those calculated in the dry aggregates case as mentioned above). On the other hand, the required mixing water added to the batch was reduced due to the existence of moisture absorbed by the coarse and fine aggregates.

After determining the amount of each ingredient of the concrete batch, a trial batch was prepared in the laboratory to check the estimated batch weights. This concrete batch had a measured slump of 3.5 inch, air content of 5.94%, and unit weight of 140.9 lb per cubic foot (pcf). Although the measured slump and air content were acceptable (<0.75 inch above 3-inch max and 1.06% below 7% max. respectively), adjustment was made to obtain exact 3-inch slump value for the control concrete batch. It is to be mentioned that this batch was cured for three days only and then tested for its compressive strength to ensure its expected properties before preparing the actual control group and allowing it to cure 28 days. The obtained compressive strength for the 3-day cured trial batch samples was 1750 psi which indicated that the expected 28-day compressive strength would be satisfactory.

After obtaining the successful control batch group, all the ingredients needed for the experimental groups were determined for the developed cementitious concrete composites containing one of the three solid waste materials at four different volume percentages (5, 10, 15, and 20%). It is to be mentioned that the only difference between designing the control group and the experimental groups was that after determining the volume of the fine aggregate needed for the control concrete group, a portion of this volume was substituted by an equivalent volume of one of the waste materials (plastics, fiberglass, or glass). Hence, the required fine aggregate content was reduced and substituted for by one of the three waste materials. However, the amount of each waste material needed to prepare the new concrete composite depended on the volume percentage and the specific gravity of this waste material. The specific gravity of each of the granulated plastics, glass, and fiberglass waste materials was determined in accordance with ASTM standards (1991g, 1988, and 1988 respectively). These values were 1.272, 2.132, and 1.365 respectively. It can be noticed here that all of these values were smaller than the value of specific gravity of sand (2.7). This means that the unit weight of any of the developed concrete composites was lower than that of the control concrete composite. Table 4 shows the weight saving percentages of the new concrete composites as compared with the control concrete batch.

Table 4

The Weight Saving Percentages of The New Concrete Composites Compared With The Unit Weight of The Control Concrete Batch

Percentage of aggregate substitute	Type of fine aggregate substitute in new cementitious concrete composite and its weight saving percentage (%)		
	Plastics	Fiberglass	Glass
5%	0.97	0.90	0.39
10%	1.95	1.82	0.79
15%	2.94	2.75	1.21
20%	3.93	3.67	1.60

It can be seen from the above table that the percent savings of the unit weight of the new cementitious concrete composites containing plastics waste material are the highest percentages followed by those containing fiberglass and glass waste materials respectively. This can be attributed to the fact that plastic waste material has lower specific gravity than that of fiberglass and glass materials. These values of percent savings indicate that reduction in the dead weight of the control concrete composite can be obtained by using solid waste materials (especially plastics) as partial aggregate substitute.

Another advantage for using solid waste materials as partial fine aggregate substitutes is their low cost compared to the cost of fine aggregate (sand). This production cost saving is especially true when the tipping fees to dispose these waste materials in landfill are considered. More production cost savings can be achieved with the increase of the volume percentage of the solid waste materials used in the cementitious concrete composite as aggregate substitute. However, one should note that the increase of the volume percentage of any of the aggregate substitute should not be unlimited. Two more factors (besides the economical factor) must also be considered to determine the optimum volume percentage of any waste material to be used as aggregate substitute in cementitious concrete composites. The first factor is the fact that the fresh mixed concrete composites should have acceptable workability, consistency, and plasticity suitable for the job conditions. The second factor is that the hardened concrete composites should be durable, meet the strength requirement, and have a uniform appearance.

The present research study revealed that the workability, consistency, and plasticity of the fresh mixtures of the developed concrete composites containing waste materials as partial fine aggregates decreased with the increase of the volume percentages of these materials. This was a general observation for all the developed concrete composites containing any of the three waste materials. However, the actual behaviors of each set of concrete composites containing one waste material were different from those containing the other two waste materials. For example, all the concrete composites containing glass waste material had satisfactory workability, consistency, and plasticity although the concrete composite containing 5% glass waste was better than that containing 10% glass (which was better than that containing 15% and so on). On the other hand, it was only the developed concrete composites containing plastics waste materials in the 5, 10, and 15% had satisfactory workability, consistency, and plasticity. The new concrete composite containing 20% plastics waste material was difficult to place and consolidate, not easy to flow, and was not easy to be molded. The developed concrete composite that contained 5 and 10% fiberglass waste material had satisfactory workability, consistency, and plasticity while those containing 15 and 20% did not have satisfactory workability, consistency, and plasticity. Table 5 shows a comparison among the developed concrete composites in terms of their workability, consistency, and plasticity.

Table 5 shows that the type and percentage of the waste fine aggregate influence the workability, consistency and plasticity of these concrete composites. As it was discussed earlier in chapter II, the fineness modulus (FM) of the fine aggregates is one of the

Table 5

The Behaviors of The New Concrete Composites in Terms of Their Workability, Consistency, and Plasticity

Percentage of aggregate substitute	Type of fine aggregate substitute in new cementitious concrete composite and its workability, consistency, and plasticity		
	Plastics	Fiberglass	Glass
5%	Yes	Yes	Yes
10%	Yes	Yes	Yes
15%	Yes	Not	Yes
20%	Not	Not	Yes

important factors that should be considered in designing concrete mixtures. The values of the (FM) of the sand, plastics waste, glass waste, and fiberglass waste materials used in the present research study were determined to be 2.7, 3.4, 2.1, and 1.6 respectively. Since the three waste materials were used to partially substitute only for 5 to 20% of the volume of sand, the values of the (FM) of these waste materials can be used (in addition to that of sand) to calculate the overall (FM) of the total fine aggregates added to the developed concrete composites. The value of the overall (FM) (FM_{Total}) of the total fine aggregates can be found from the following equation:

$$FM_{Total} = (p)\,(FM_{WM}) + (1\text{-}p)\,(FM_{FA}) \qquad (16)$$

where (p) is the volume percentage of the aggregate substitute, and (FM_{WM}) and (FM_{FA}) are the fineness modulus of the waste material and fine aggregate (sand) used in each of the developed cementitious concrete composites.

Table 6 shows the calculated values of the (FM_{Total}) of the developed concrete composites. As it can be seen from this table, adding waste materials as partial aggregate substitutes for the sand in the concrete composites changes the overall FM than that of the control concrete mixture. This change, of course, has a direct effect on the workability, consistency, and plasticity of the new concrete composites. This may be attributed to the fact that the FM of the fine aggregates influences the amounts of coarse aggregate, fine aggregate, and water needed in the concrete mixtures to obtain the desired properties. Since the present research study concentrated only on substituting certain percentages of sand with equivalent percentages of one of the three waste materials, no changes have been made to the other ingredients (water, cement, and gravel) of the concrete composites.

The values of the overall (FM) for the new concrete composites, shown in Table 6, deduce expected variations in the behaviors of the concrete composites containing plastics waste than those containing glass or fiberglass wastes. Since the value of (FM) for plastics waste material used in this study was higher than that of sand (3.4 to 2.7 respectively), the overall (FM) for concrete composites containing plastics waste increased with the increase of the volume percentage of plastics in these composites. From the concrete mix design point of view, both the gravel and water contents were supposed to be reduced while the sand and plastics waste contents were supposed to be increased. Of course, no adjustment was made and consequently the characteristics of the new concrete composites were greatly varied specially for those composites with high percentages (15% and 20%). However, for the concrete composite containing a volume of 15% plastics waste, the workability, plasticity, and consistency were barely satisfactory while for that containing 20% these properties were not satisfactory.

It can be observed from Tables 5 and 6 that the new concrete composite, which had an overall (FM) value of the fine aggregates (80% sand and 20% plastics waste) of 2.84, was not satisfactory. This value of (FM) was higher than that of the control concrete composite (100% sand fine aggregate) by more than 5%. The tables also show that both the new concrete composites containing 15 and 20% fiberglass waste material were not satisfactory. The values of the overall (FM) of the fine aggregates containing these two percentages were 2.54 and 2.48 respectively. These values were below that of control concrete composite (100% sand) by more than 5%. Therefore, it can be concluded that the fineness modulus of the total fine aggregates (sand and any waste materials) used in new concrete composites should not be higher or lower than that of the control concrete composite (100% sand) by more than 5%. This conclusion is enhanced by the values of the (FM) obtained for the fine aggregates (sand and 5, 10, 15, or 20% glass waste) where these values (2.67, 2.64, 2.61, and 2.58 respectively) did not exceed 5% below the value of 100% sand and all the developed concrete composites containing this waste material were satisfactory. It is to be mentioned that all the combinations of the fine aggregates used in concrete composites developed in this study (sand and plastics, glass, or fiberglass) had values of overall (FM) between about 2.48 and 2.84. These values are in accordance with ASTM C33 standard (1991j). In other words, these values of the overall (FM) should neither be less than 2.3 nor more than 3.1.

Table 6

The Value of The Overall Fineness Modulus of The Total Fine Aggregates Used in The New Cementitious Concrete Composites

Percentage of aggregate substitute	Type of fine aggregate substitute in new cementitious concrete composite and its fineness modulus (FM)		
	Plastics	Fiberglass	Glass
5%	2.74	2.65	2.67
10%	2.77	2.59	2.64
15%	2.81	2.54	2.61
20%	2.84	2.48	2.58

Testing Results of the Cementitious Concrete Composites

As it was mentioned previously, three mechanical testing methods were conducted in the present research study to calculate four properties of the developed cementitious concrete composites: compressive strength, splitting tensile strength, modulus of rupture, and modulus of elasticity. All these tests were in accordance with the ASTM standards (1991b, 1991c, and 1991d respectively). The results obtained from each of these tests for the control and developed cementitious concrete composites are presented below. Also a comprehensive discussion for the obtained results follows.

Compressive Strength Test

It has been pointed out that the compressive strength (f'_c) of concrete is a primary mechanical property which is usually used in the design calculations for such applications as pavements, bridges, buildings, and other structures (Kosmatka & Panarese, 1988). It can be defined as the maximum resistance of a concrete mixture to axial loading and generally expressed in pounds per square inch (psi) at a curing period of 28 days. In the present research study, a general-use concrete composite of a specified (f'_c) of 3000 psi was considered. The testing method used to determine the values of (f'_c) for the control and new cementitious concrete composites were based on the ASTM C39-86 standard (1991b). A hydraulic Soil Test Versa-Tester (Model 30-K machine) with a maximum applied force of 60,000 lb (available in the Production and Material Testing laboratories in the Department of Industrial Technology, UNI) was used for this purpose. The values of (f'_c) for the control and new cementitious concrete composites were obtained by applying a compressive axial load to the molded concrete cylinders (3" of diameter by 6" of length) at a rate of 20 to 50 psi/s (or about 140 to 350 lbs/s) until failure occurs. Five specimens were tested for each concrete composite to determine the average (f'_c) for that composite. Figure 6 shows a molded concrete cylinder being axially loaded during the compression test. The compressive strength (f'_c) of each of the test specimens was calculated as follows (equation 17):

$$f'_c = P / A \quad \text{(psi)} \qquad (17)$$

where (P) is the maximum applied load (lb) and (A) is the circular cross-sectional area of the specimen (in^2). Table 7 shows the maximum applied loads and the corresponding (f'_c) values for all the tested specimens of the control group. Table 8 shows the values of (f'_c) and standard deviations for all the tested specimens of the new cementitious concrete composites containing plastics, glass, and fiberglass at different volume percentages. Complete information for the collected data can be seen in Appendix A. The analysis of the obtained results is outlined in the following sections.

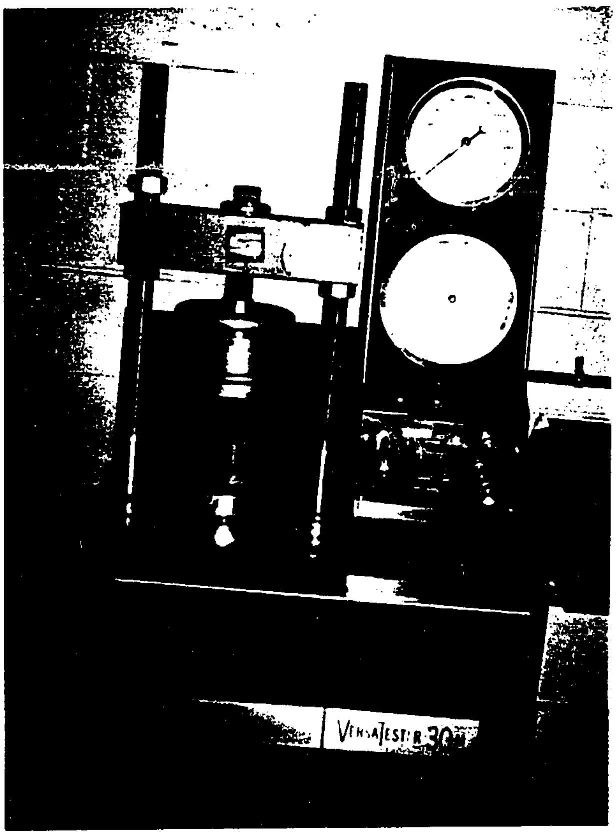


Figure 6. A molded concrete cylinder being axially loaded during the compression test.

Table 7

The Maximum Applied Loads and Corresponding Compressive Strengths of The Control Cementitious Concrete Composite

Sample Number	1	2	3	4	5	Average value	Standard Deviation
Load (lb)	35670	37510	32000	42050	41180	37680	4110
Strength (psi)	5050	5310	4530	5950	5830	5330	580

Table 8

The Average Compressive Strengths and Standard Deviations For The New Concrete Composites Containing Plastics, Glass, and Fiberglass at Different Volume Percentages

Percentage of aggregate substitute	Type of fine aggregate substitute in new cementitious concrete composite and the average compressive strength (psi) and the standard deviation for this composite		
	Plastics specimens	Fiberglass specimens	Glass specimens
5%	250 4420	220 4450	600 4300
10%	220 3860	200 4020	460 4080
15%	400 3280	310 3800	400 4050
20%	120 4090	620 3200	160 5040

Control cementitious concrete composite. Table 7 shows the maximum applied loads and corresponding (f'_c) of the five tested specimens for the control cementitious concrete composite. It can be seen from this table that the average (f'_c) for this composite is 5330 psi with a standard deviation of 580 psi. This value of (f'_c) is higher than both the specified and required compressive strengths (3000 and 4200 psi respectively) of the control concrete composite. In other words, the hardened control concrete composite is accepted from the durability point of view since it meets the strength requirement, and had a uniform appearance). This is in addition to the fact that the fresh mix of the tested control concrete had workability, consistency, and plasticity suitable for the job conditions.

Plastics-containing cementitious concrete composites. Table 8 shows the values of (f'_c) and standard deviation for the new concrete composites containing plastics, glass, and fiberglass at different volume percentages. It can be seen from this table that at 5% plastics aggregate substitute, the average (f'_c) is 4420 psi with a standard deviation of 250 psi. This value of (f'_c) is higher than the specified (f'_c = 3000 psi) of the control concrete composite by about 47% which makes this composite acceptable. Furthermore, this composite is lighter in weight than the control composite by 0.97% as can be seen in Table 4. However, according to the actual obtained (f'_c) for the control concrete composite, the (f'_c) of the concrete composite with 5% plastics waste aggregate is 17% lower than the counterpart for the control concrete composite.

Table 8 also shows that at 10% plastics aggregate substitute, the average (f'_c) is 3860 psi with a standard deviation of 220 psi. This value of (f'_c) is higher than the specified one of the control concrete composite by about 29% which makes this composite still durable. In addition, the weight of this composite is less than that of the control composite by 1.95%. But, the (f'_c) of the concrete composite containing 10% plastics waste aggregate is 28% lower than its counterpart of the obtained control concrete composite. Similarly, the average (f'_c) of the new concrete composite containing 15% plastics waste aggregate (3280 psi with a standard deviation of 400 psi) is higher than the specified (f'_c)c of the control concrete composite by about 9% which makes this composite barely satisfactory in terms of durability as well as workability, consistency, and plasticity.

The weight saving for this composite over that of the control concrete composite is 2.94%. On the other hand, ($\underline{f'_c}$) of this concrete composite is 38% lower than that of the obtained control concrete composite.

At 20% plastics waste aggregate substitute, the average ($\underline{f'_c}$) is 4090 psi with a standard deviation of 120 psi. This value of ($\underline{f'_c}$) is higher than the specified one of the control concrete composite by about 36% which makes this composite still durable. The weight saving for this composite is 3.93% compared to that of control concrete composite. On the other hand, the value of ($\underline{f'_c}$) of this concrete composite is 23% lower than that of the obtained control concrete composite. Based on the experimental experience and observation, this concrete composite was not satisfactory from the workability, consistency, and plasticity point of view as it has been mentioned before.

Fiberglass-containing cementitious concrete composites. Table 8 shows the values of ($\underline{f'_c}$) and standard deviation for the new cementitious concrete composites containing fiberglass waste aggregate at different volume percentages. Again, at 5% fiberglass aggregate substitute, the average ($\underline{f'_c}$) is 4450 psi with a standard deviation of 220 psi. This value of ($\underline{f'_c}$), which is almost identical to that composite contained 5% plastics waste, is higher than the specified ($\underline{f'_c}$) (3000 psi) of the control concrete composite by about 48% which makes this composite acceptable. Furthermore, the weight saving of this composite is 0.90% compared to the control composite. On the other hand, the actual ($\underline{f'_c}$) obtained for the control concrete composite has dropped by 17% due to the existence of 5% fiberglass waste as aggregate substitute.

When 10% fiberglass was added as aggregate substitute, the average ($\underline{f'_c}$) was dropped to 4020 psi with a standard deviation of 200 psi. This value of ($\underline{f'_c}$), which is very close to that composite contained 10% plastics waste, is still higher than the specified one of the control concrete composite by about 34% which makes this composite still durable. In addition, the weight of this composite is less than that of control composite by 1.82%. But, the ($\underline{f'_c}$) of the concrete composite containing 10% fiberglass waste aggregate is 25% lower than the counterpart of the obtained control concrete composite.

Table 8 shows that the average (f'_c) of the 15% fiberglass concrete composite is 3800 psi with a standard deviation of 310 psi. This value of the (f'_c) is higher than the specified one of the control concrete composite by about 27% which makes this composite acceptable in terms of durability. The weight saving for this composite over that of the control composite is 2.75%. On the other hand, the (f'_c) of this concrete composite is 29% lower than that of the obtained control concrete composite. Table 8 also shows that at 20% fiberglass aggregate substitute, the average (f'_c) has dropped to the lowest value (3200 psi with a standard deviation of 620 psi). This value of (f'_c) is higher than the specified one of the control concrete composite by only 7% which makes this composite allowable. It can also be noticed in Table 8 that 3 out of the 5 tested specimens of this composite had (f'_c) values below the specified one of the control concrete composite. However, the weight saving for this composite has the highest value (3.67% over that of the control concrete composite) among the different four aggregate percentages used in this study. On the other hand, the (f'_c) of this concrete composite is 40% lower than that of the obtained control concrete composite. Therefore, and based on the experimental experience and observations, the concrete composites which contained 15 and 20% fiberglass waste aggregate were not as good as those composites containing 5 and 10% fiberglass waste aggregate from the workability, consistency, and plasticity point of view.

Glass-containing cementitious concrete composites. Table 8 shows the values of (f'_c) and standard deviation for the new concrete composites containing glass at different volume percentages. It can be seen from this table that at 5% glass aggregate substitute, the average (f'_c) is 4300 psi with a standard deviation of 600 psi. This value of (f'_c) is higher than that for the specified one of the control concrete composite by about 43% which makes this composite acceptable. Furthermore, this composite is lighter in weight than the control composite by 0.39% as it can be seen in Table 4. However, according to the actual obtained (f'_c) for the control concrete composite, the (f'_c) of the concrete composite with 5% glass waste aggregate is 19% lower than the counterpart for the control composite.

At 10% glass aggregate substitute, the average (f'_c) is 4080 psi with a standard deviation of 460 psi. This value of (f'_c) is higher than the specified one of the control concrete composite by about 36% which makes this composite still durable. In addition, the weight of this composite is less than that of the control composite by 0.79%. But, the ($\underline{f'_c}$) of the concrete composite containing 10% glass waste aggregate is 23% lower than the counterpart of the obtained control concrete composite. Similarly, the average ($\underline{f'_c}$) of the new concrete composite containing 15 and 20% glass waste aggregate (4050 psi with a standard deviation of 400 psi and 5040 psi with a standard deviation of 160 psi respectively) are higher than the specified one of the control concrete composite by about 35% and 68% respectively. This makes both composites acceptable in terms of durability as well as workability, consistency, and plasticity. The weight savings for these composites over that of the control concrete composite is 1.21% and 1.60 respectively. On the other hand, the ($\underline{f'_c}$) of these concrete composites are 24% and 5% (respectively) lower than that of the obtained control concrete composite.

Splitting Tensile Strength Test

It has been mentioned earlier that the splitting tensile strength ($\underline{T}$) is a measure which is usually used to evaluate the shear resistance provided by concrete composites in reinforced lightweight aggregate concrete members. This measure is simpler to determine than direct tensile strength. The testing method which is used to determine the ($\underline{T}$) values for all the tested cementitious concrete composites was based on the ASTM C496-90 standard (1991c). This value was obtained by applying a continuous diametral compressive force at a constant rate (100 to 200 psi/min or about 2850 to 5700 lbs/min) to a cylindrical concrete specimen (3" of diameter by 6" of length). After measuring the actual dimensions of each specimen, this specimen was placed with its axis horizontal between the bearing blocks of the testing machine as shown in Figure 7. This machine was a hydraulic SoilTest Versa-Tester (Model 30-K machine) with a maximum applied force of 60,000 lb (available in the Production and Material Testing laboratories in the Department of Industrial Technology, UNI). The maximum applied load indicated by the testing machine at failure was recorded. Then, the splitting tensile strength ($\underline{T}$) was computed as follows (equation 18):

$$\underline{T} = 2\,P / (\pi\, l\, d) \qquad \text{(psi)} \qquad (18)$$

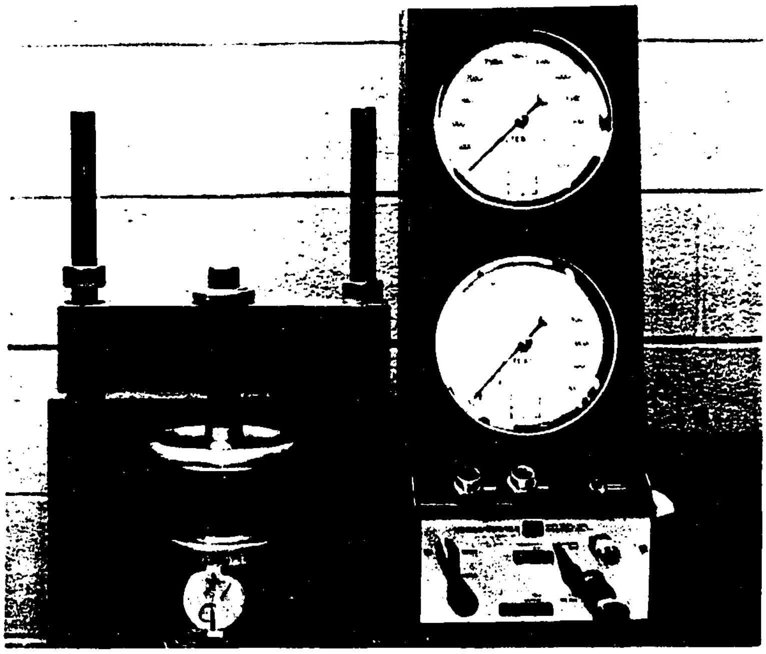


Figure 7. A molded concrete cylinder tested under splitting tensile load.

Table 9

The Maximum Applied Loads and Corresponding Splitting Tensile Strengths of The Control Cementitious Concrete Composite

Sample Number	1	2	3	4	5	6	Average value	Standard Deviation
Load (lb)	13050	13340	15660	17010	15850	18370	15550	2060
Strength (psi)	470	490	575	605	580	660	565	70

Where (P) is the maximum applied load (lb) and (l and d) are the length and diameter of the cylinder (in inches) respectively. Table 9 shows the maximum applied loads and the corresponding (T) for all the tested specimens of the control group. On the other hand, Table 10 shows the values of (T) and standard deviations for all the tested specimens of the new cementitious concrete composites containing plastics, glass, and fiberglass at different volume percentages. Complete information about the collected data can be seen in appendix B. The analysis of the obtained results is outlined in the following sections.

Table 10

The Splitting Tensile Strengths and Standard Deviation for The New Cementitious Concrete Composites Containing Plastics, Glass, and Fiberglass at Different Volume Percentages

Percentage of aggregate substitute	Type of fine aggregate substitute in new cementitious concrete composite and the average splitting tensile strength (psi) and the standard deviation for this composite		
	Plastics specimens	Fiberglass specimens	Glass specimens
5%	450 ^{60}	495 ^{60}	495 ^{75}
10%	430 ^{45}	500 ^{45}	480 ^{20}
15%	450 ^{50}	480 ^{30}	435 ^{50}
20%	440 ^{60}	470 ^{35}	485 ^{25}

<u>Control cementitious concrete composite</u>. Table 9 shows the maximum applied loads and corresponding (<u>T</u>) of the six tested specimens for the control concrete composite. It can be seen from this table that the average (<u>T</u>) for this composite is 565 psi with a standard deviation of 70 psi. This value of (<u>T</u>) is about 10.6% of the obtained (<u>f'c</u>) (5330 psi) of the control concrete composite. Kosmatka and Panarese (1988) has pointed out that the (<u>T</u>) of concrete is about 8% to 12% of the (<u>f'c</u>) and is often estimated as 5 to 7.5 times the square root of the (<u>f'c</u>). The obtained (<u>T</u>) for the control concrete composite conforms with the expected range (8% to 12%).

<u>Plastics-containing cementitious concrete composites</u>. Table 10 shows the values of (<u>T</u>) and standard deviation for the new concrete composites containing plastics waste at different volume percentages. It can be seen from this table that at 5% plastics aggregate substitute, the average (<u>T</u>) is 440 psi with a standard deviation of 60 psi. This value of (<u>T</u>) is about 10% of the obtained (<u>f'c</u>) (4420 psi) of the new concrete composite containing 5% plastics waste aggregate. On the other hand, this value of (<u>T</u>) is lower than the counterpart for the control concrete composite by about 22%. Table 10 also shows that at 10% plastics aggregate substitute, the average (<u>T</u>) is 430 psi with a standard deviation of 45 psi. This value of (<u>T</u>) is lower than the counterpart for the control concrete composite by about 24%. In addition, this value of (<u>T</u>) is about 11% of the obtained (<u>f'c</u>) (3860 psi) of the new concrete composite containing 10% plastics waste aggregate. This value of (<u>T</u>) is slightly lower than that composite containing 5% plastics waste aggregate by about 2.3%.

Similarly, the average (<u>T</u>) of the new concrete composite containing 15% plastics waste aggregate (450 psi with a standard deviation of 50 psi) is lower than that of the control concrete composite by about 20% which makes this composite slightly better than those with 5% and 10% plastics waste aggregate. On the other hand, the ratio between the (<u>T</u>) and (<u>f'c</u>) of this concrete composite is 14%. This ratio exceeds the maximum expected ratio mentioned by Kosmatka and Panarese (1988) by 2%. At 20% plastics waste aggregate substitute, the average (<u>T</u>) is 440 psi with a standard deviation of 60 psi. This (<u>T</u>) value is similar to the obtained value for that composite containing 5% plastics waste.

Fiberglass-containing cementitious concrete composites. Table 10 also shows the values of (T) and standard deviation for the concrete composites containing fiberglass waste at different volume percentages. It can be seen from this table that at 5% fiberglass aggregate substitute, the average (T) is 495 psi with a standard deviation of 60 psi. This value of (T) is about 11% of the obtained f'c (4450 psi) of the same concrete composite. On the other hand, this value of (T) is lower than its counterpart for the control concrete composite by about 12.4%. Furthermore, table 10 shows that at 10% fiberglass aggregate substitute, the average (T) is 500 psi with a standard deviation of 35 psi. This value of T is lower than its counterpart for the control concrete composite by about 11.5%. In addition, this value of T is about 12% of the obtained f'c (4020 psi) of the same concrete composite. This value of T is almost identical to that composite containing 5% fiberglass aggregate.

Similarly, the average (T) of the new concrete composite containing 15% fiberglass waste aggregate (480 psi with a standard deviation of 30 psi) is lower than that of the control concrete composite by about 15% which makes this composite not as good as those containing 5% and 10% fiberglass waste aggregate. On the other hand, the (T/f'c) ratio of this concrete composite is 13%. This ratio exceeds the maximum expected ratio mentioned by Kosmatka and Panarese (1988) by 1%. At 20% fiberglass waste aggregate substitute, the average (T) is 470 psi with a standard deviation of 35 psi. This value of (T) is the lowest value obtained among the different waste percentage used in this study. It is also lower than that of the control concrete composite by about 17%. On the other hand, the (T/f'c) ratio of this concrete composite is about 15%. This ratio exceeds the maximum expected ratio mentioned by Kosmatka and Panarese (1988) by 3%.

Glass-containing cementitious concrete composites. Table 10 shows the values of (T) and standard deviation for the new cementitious concrete composites containing glass at different volume percentages. It can be seen from this table that at 5% glass aggregate substitute, the average (T) is 495 psi with a standard deviation of 75 psi. This value of (T), which is similar to the counterpart containing 5% fiberglass waste aggregate, is about 11% of the obtained (f'c) (4300 psi) of the same concrete composite. On the other hand, this value of (T) is lower than its counterpart for the control concrete composite by about 12.4%. Table 10 also shows that at 10% glass aggregate substitute, the average (T) is 480 psi with a standard deviation of 20 psi. This value of (T) is lower than the counterpart for the control concrete composite by about 15%. In addition, this value of (T) is about 12% of the obtained (f'_c) (4080 psi) of the same concrete composite. This value of T is slightly lower than that of the composite containing 5% glass waste aggregate by about 2.6%.

The average (T) of the new concrete composite containing 15% glass waste aggregate (435 psi with a standard deviation of 50 psi) is lower than that of the control concrete composite by about 23% which makes this composite not as good as those with 5% and 10% glass waste aggregate. On the other hand, the (T/f'_c) ratio of this concrete composite is 11%. This ratio is within the expected range given by Kosmatka and Panarese (1988). At 20% glass waste aggregate substitute, the average (T) is 485 psi with a standard deviation of 25 psi. This value of (T) is in between the obtained values for the concrete composites containing 5% and 10% glass waste aggregates. On the other hand, this value of (T) is lower than its counterpart for the control concrete composite by about 14%. Also, the (T/f'_c) ratio of this concrete composite is 10%.

Flexural Strength Test

It is a fact that flexural strength and the modulus of elasticity of concrete are generally used in designing pavements and other slabs on ground. In the present research study, all the test specimens and testing procedure were in conformance to all requirements of ASTM C293-79 standard (1991d). An applied test system (ATS) with a 5000 lb maximum force, Series 900 UTM (universal test machine) with an X-Y recorder (both were available in the production and material testing laboratories in the Department of Industrial Technology, UNI) was used for this purpose. The loading configuration of a tested specimen is shown in Figure 8. The test specimen was loaded continuously and without shock at a constant rate (125 to 175 psi/min or about 110 to 160 lbs/min) until rupture occurs. It is to be mentioned here, that the X-Y recorder was used to generate the load-deflection curve for the tested specimen. Also, the testing machine had the capability to read both the maximum applied load and deflection. These values and the dimensions of the specimen were recorded and then used to calculate both the modulus of rupture (R) and the flexural modulus of elasticity (E) as shown in equations 19 and 20:

$$\underline{R} = (3\,P\,l)\,/\,(2\,b\,d^2) \qquad \text{(psi)} \qquad (19)$$

$$\underline{E} = (P\,l^3)\,/\,(4\,\delta\,b\,d^3) \qquad \text{(Ksi)} \qquad (20)$$

Where (P) is the maximum applied load (lb), (l) is the span length of the beam (in), (b) is the average width of the tested specimen at the point of fracture (in), (d) is the average depth of specimen at the point of fracture (in), and (δ) is the maximum deflection at the center point of the specimen at fracture (inch). Table 11 shows the maximum applied loads and corresponding (R) for all the tested specimens of the control concrete composite. Table 12 shows the values of (R) and standard deviations for the new cementitious concrete composites containing plastics, glass, and fiberglass at different volume percentages. On the hand, Table 13 shows the maximum applied loads and corresponding (E) for all the tested specimens of the control concrete composite. Finally, Table 14 shows the values of (E) and standard deviations for the new cementitious concrete composites containing plastics, glass, and fiberglass at different volume percentages. Complete information for the collected data can be seen in Appendix A. The analysis of the obtained results is outlined in the following sections.

Control cementitious concrete composite. Table 11 shows the maximum applied loads and corresponding (R) of the five tested specimens for the controlled cementitious concrete composite. It can be seen from this table that the average (R) for this composite is 880 psi with a standard deviation of 45 psi. This value of (R) is about 12 times the square root of the obtained (f'c = 5330 psi) of the control concrete composite. Kosmatka and Panarese (1988) has indicated that the (R) value of normal-weight concrete is often approximated as 7.5 to 10 times the square root of the (f'c). The obtained (R) for the control concrete composite is higher than the maximum expected value given by Kosmatka and Panarese (1988) by 2 times the square root of the obtained (f'c).

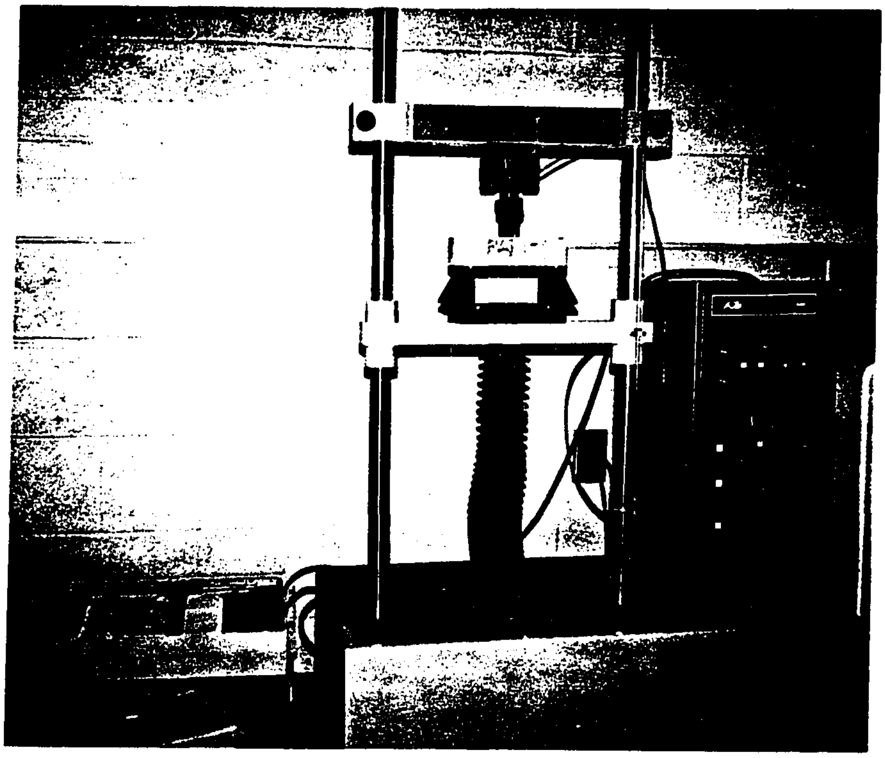


Figure 8. A tested specimen being axially loaded during the flexural test.

Table 11

The Maximum Applied Loads and Corresponding Modulus of Ruptures of The Control Cementitious Concrete Composite

Sample Number	1	2	3	4	5	Average value	Standard Deviation
Load (lb)	715	740	800	755	855	775	55
R (psi)	845	850	905	850	940	880	45

Table 12

The Modulus of Ruptures and Standard Deviations for The New Cementitious Concrete Composites Containing Plastics, Glass, and Fiberglass at Different Volume Percentages

Percentage of aggregate substitute	Type of fine aggregate substitute in new cementitious concrete composite and the average modulus of rupture (psi) and the standard deviation for this composite		
	Plastics specimens	Fiberglass specimens	Glass specimens
5%	85 945	50 820	100 910
10%	40 800	50 805	60 875
15%	35 650	45 745	50 820
20%	75 635	20 760	65 910

Plastics-containing cementitious concrete composites. Table 12 shows the average values of (R) and standard deviation for the new cementitious concrete composites containing plastics at different volume percentages. It can be seen from this table that at 5% plastics aggregate substitute, the average (R) is 945 psi with a standard deviation of 85 psi. This value of (R) is about 14 times the square root of the obtained (f'_c = 4420 psi) of the same concrete composite. This value is higher than the maximum expected value given by Kosmatka and Panarese (1988) by 4 times the square root of the obtained (f'_c). In addition, this value of (R) is higher than the counterpart for the control concrete composite by about 7%. Table 12 also shows that at 10% plastics aggregate substitute, the average (R) is 800 psi with a standard deviation of 40 psi. This value of (R) is lower than the counterpart for the control concrete composite by about 9%. In addition, this value of (R) is about 13 times the square root of the obtained (f'_c = 3860 psi) of the same concrete composite. This value is higher than the maximum expected value given by Kosmatka and Panarese (1988) by 3 times the square root of the obtained (f'_c). This (R) value is lower than that value of composite containing 5% plastics waste aggregate by more than 15%.

Similarly, the average (R) of the new concrete composite containing 15% plastics waste aggregate (650 psi with a standard deviation of 35 psi) is lower than that of the control concrete composite by about 26% which makes this composite not as good as those with 5 and 10% plastics waste aggregate. On the other hand, the ratio between the (R) value and square root of the obtained (f'_c) of this concrete composite is 11. This ratio exceeds the maximum expected ratio mentioned by Kosmatka and Panarese (1988) by one. At 20% plastics waste aggregate substitute, the average (R) is 635 psi with a standard deviation of 75 psi. This value of (R) is the lowest obtained value among the four composites contained plastics waste aggregate. It is also lower than that of the control concrete composite by about 28%. On the other hand, the ratio between the (R) value and square root of the obtained (f'_c) of this concrete composite is 10.

Fiberglass-containing cementitious concrete composites. Table 12 shows the values of R and standard deviations for the fiberglass-containing concrete composites at different volume percentages. It can be seen from this table that at 5% fiberglass aggregate substitute, the average R is 820 psi with a standard deviation of 50 psi. This R value is over 12 times the square root of the obtained (f'_c) of the same concrete composite. This ratio exceeds the maximum expected ratio mentioned by Kosmatka and Panarese (1988) by about 2 times the square root of the obtained f'_c. On the other hand, this R value is lower than its counterpart for the control concrete composite by about 7%. Table 12 also shows that at 10% fiberglass aggregate substitute, the average R is 805 psi with a standard deviation of 50 psi. This value of R is lower than the counterpart for the control concrete composite by about 9%. In addition, this value of R is about 12.6 times the square root of the obtained (f'_c = 4020 psi) of the same concrete composite. This value of R is almost identical to that value of the concrete composite containing 5% fiberglass waste aggregate.

Similarly, the average R of the new concrete composite containing 15% fiberglass waste aggregate (745 psi with a standard deviation of 45 psi) is lower than that of the control concrete composite by about 15% which makes this composite not as good as those with 5% and 10% fiberglass waste aggregate. On the other hand, the ratio between the R value and square root of the obtained f'c of this concrete composite is about 12. This ratio exceeds the maximum expected ratio mentioned by Kosmatka and Panarese (1988) by two. At 20% fiberglass waste aggregate substitute, the average R is 760 psi with a standard deviation of 20 psi. This value of R is close to that of the new concrete composite containing 15% fiberglass waste aggregate. However, it is lower than that of the control concrete composite by about 14%. On the other hand, the ratio between the R value and square root of the obtained f'c of this concrete composite is about 13.4. This ratio exceeds the maximum expected ratio mentioned by Kosmatka and Panarese (1988) by 3.4.

Glass-containing cementitious concrete composites. Table 12 shows the values of R and standard deviations for the new cementitious concrete composites containing glass waste at different volume percentages. It can be seen from this table that at 5% glass aggregate substitute, the average (R) is 910 psi with a standard deviation of 100 psi. This value of (R) is about 14 times the square root of the obtained (f'c = 4300 psi) of the same concrete composite. This ratio exceeds the maximum expected ratio mentioned by Kosmatka and Panarese (1988) by about 4 times the square root of the obtained (f'c). On the other hand, this value of (R) is higher than its counterpart for the control concrete composite by about 3.4%. Table 12 also shows that at 10% glass aggregate substitute, the average (R) is 875 psi with a standard deviation of 60 psi. This value of (R) is almost identical to that value for the control concrete composite. In addition, this value of (R) is about 14 times the square root of the obtained (f'c = 4080 psi) of the same concrete composite. This ratio exceeds the maximum expected ratio (Kosmatka & Panarese, 1988) by about 4 times the square root of the obtained (f'c). This value of (R) is slightly lower than that composite containing 5% glass waste aggregate by about 3.8%.

The average (R) of the new concrete composite containing 15% glass waste aggregate (820 psi with a standard deviation of 50 psi) is lower than that of the control concrete composite by about 7% which makes this composite not as good as those with 5% and 10% glass waste aggregate. On the other hand, the ratio between (R) and square root of the obtained ($\underline{f'_c}$) of this concrete composite is 13%. This ratio exceeds the maximum expected ratio (Kosmatka & Panarese, 1988) by about 3 times the square root of the obtained ($\underline{f'_c}$). At 20% glass waste aggregate substitute, the average ($\underline{R}$) is 910 psi with a standard deviation of 65 psi. This value of ($\underline{R}$) is similar to the obtained value for the concrete composites containing 5% glass waste aggregate. It is also about 13 times the square root of the obtained ($\underline{f'_c}$ = 5040 psi) of the same concrete composite. This ratio exceeds the maximum expected ratio by about 3 times the square root of the obtained ($\underline{f'_c}$).

Table 13

<u>The Maximum Applied Loads and Corresponding Modulus of Elasticities of The Control Cementitious Concrete Composite</u>

Sample Number	1	2	3	4	5	Average value	Standard Deviation
Load (lb)	715	740	800	755	855	775	55
E (Ksi)	45.50	69.65	92.09	60.43	68.86	67.31	16.92

<u>Control cementitious concrete composite</u>. Table 13 shows the maximum applied loads and corresponding ($\underline{E}$) of the five tested specimens for the control concrete composite. It can be seen from this table that the average ($\underline{E}$) for this composite is 67.31 Ksi with a standard deviation of 16.92 Ksi.

<u>Plastics-containing cementitious concrete composites</u>. Table 14 shows the values of $\underline{E}$ and standard deviations for the new cementitious concrete composites containing plastics at different volume percentages. It can be seen from this table that at 5% plastics aggregate substitute, the average ($\underline{E}$) is 99.40 Ksi with a standard deviation of 28.55 Ksi. This value of ($\underline{E}$) is higher than its counterpart for the control concrete composite by about 48%.

Table 14

The Values of E and Standard Deviations for The New Cementitious Concrete Composites Containing Plastics, Glass, and Fiberglass at Different Volume Percentages

Percentage of aggregate substitute	Type of fine aggregate substitute in new cementitious concrete composite and the average modulus of elasticity (Ksi) and the standard deviation for this composite		
	Plastics specimens	Fiberglass specimens	Glass specimens
5%	28.55 99.40	12.90 81.60	15.55 71.65
10%	13.62 70.65	18.37 90.93	5.73 62.54
15%	5.92 62.35	27.49 90.26	12.2 82.19
20%	9.37 61.82	16.88 81.81	8.12 90.57

Table 14 also shows that at 10% plastics aggregate substitute, the average (E) is 70.65 Ksi with a standard deviation of 13.62 Ksi. This value of (E) is higher than its counterpart for the control composite by about 5%. On the other hand, this (E) value is lower than that value of composite containing 5% plastics waste aggregate by about 29%.

Similarly, the average (E) of the new concrete composite containing 15% plastics waste aggregate (62.35 Ksi with a standard deviation of 5.92 Ksi) is lower than that of the control concrete composite by about 7% which makes this composite not as good as those with 5 and 10% plastics waste aggregate. At 20% plastics waste aggregate substitute, the average (E) is 61.82 Ksi with a standard deviation of 9.37 Ksi. This value of (E), which seems to be similar to that composite containing 15% plastics waste, is lower than that of the control concrete composite by about 8%.

<u>Fiberglass-containing cementitious concrete composites</u>. Table 14 shows the values of (E) and standard deviations for the new cementitious concrete composites containing fiberglass at different volume percentages. It can be seen from this table that at 5% fiberglass aggregate substitute, the average E is 81.60 Ksi with a standard deviation of 12.90 Ksi. This value of E is higher than its counterpart for the control concrete composite by about 21%. Table 14 also shows that at 10% fiberglass aggregate substitute, the average (E) is 90.93 Ksi with a standard deviation of 18.37 Ksi. This (E) value is higher than the counterpart for the control composite by about 35%. It is also higher than that value of the concrete composite containing 5% fiberglass waste aggregate by about 11%.

The average (E) of the new concrete composite containing 15% fiberglass waste aggregate (90.86 Ksi with a standard deviation of 27.49 Ksi) is higher than that of the control concrete composite by about 35% which makes this composite almost identical to that with 10% fiberglass waste aggregate. At 20% fiberglass waste aggregate substitute, the average (E) is 81.81 Ksi with a standard deviation of 16.88 Ksi. This value of (E) is almost identical to that of the new concrete composite containing 5% fiberglass waste aggregate. However, it is lower than that of those concrete composites containing 5 and 10% fiberglass aggregates by about 11%.

<u>Glass-containing cementitious concrete composites</u>. Table 14 shows the values of (E) and standard deviations for the new cementitious concrete composites containing glass waste at 5, 10, 15, 20%. It can be seen from this table that at 5% glass aggregate substitute, the average (E) is 71.65 Ksi with a standard deviation of 15.55 Ksi. This value of (E) is about 6% higher than its counterpart for the control concrete composite. Table 14 also shows that at 10% glass aggregate substitute, the average (E) is 62.54 Ksi with a standard deviation of 5.73 Ksi. This (E) value is lower than its counterpart for the control concrete composite by about 7%. In addition, this value of (E) is about 13% lower than that composite containing 5% glass waste aggregate.

The average (E) of the new concrete composite containing 15% glass waste aggregate (82.19 Ksi with a standard deviation of 12.20 Ksi) is higher than that of the control concrete composite by about 22% which makes this composite stiffer than those with 5% and 10% glass waste aggregate. At 20% glass waste aggregate substitute, the average (E) is 90.57 Ksi with a standard deviation of 8.12 Ksi. This value of (E) is the highest obtained value among the developed concrete composites containing glass waste aggregate. It is higher than that of the control concrete composite by about 35%.

Statistical Analysis For The Obtained Results

All the quantitative results obtained from the experimentation of this research study were statistically analyzed. Based on Research Questions 1 through 6, which were stated in chapter I, three methods and tests of analysis were used to compare and discuss the recorded data. The first statistical analysis method was a two-way factor using the percentage and type of aggregate substitute as a two-way analysis of variance (Two-Way ANOVA). This method was used to determine whether the types and percentages of aggregate substitutes as well as their interaction have any significant effects on each of the mechanical properties of the new cementitious concrete composites. The second statistical analysis method was the one-way analysis of variance (One-Way ANOVA). This method was basically used to determine whether there were significant differences among the values of the mechanical properties of the control concrete composite and those values for the new concrete composites containing different percentages of aggregate substitutes. Finally, an appropriate post hoc test (Tukey HSD procedure) was used to identify any significant differences among the control and new concrete composites containing different percentages of aggregate substitutes. This test was used because of the many hypotheses involved in this study needed to be tested and multiple comparisons needed to be conducted. It is to be mentioned that graphical representation and analysis for the obtained results are also included to compare the developed cementitious concrete composites with the control concrete composite.

Compressive Strength

The values of the calculated (f'_c) for all the tested specimens of the 12 developed concrete composites (i.e. plastics, glass, and fiberglass at 5, 10, 15, and 20% each) were used as data base for the statistical analysis part in this research study. An SPSS computer software package was used to analyze these data which were prepared as a two-way factor using the percentage and type of aggregate substitute as a two-way ANOVA method. Appendix E shows a list of the arrangement of these data. Table 15 shows the average statistical values of ($\underline{f'_c}$) for each new concrete composite at different percentages and the number of tested specimens. It is to be noted here that these values are not rounded as those values shown in Table 8 (which are in accordance with ASTM standard, 1991b) because of the nature of the statistical treatment. Table 15 shows also the average ($\underline{f'_c}$) values for the total groups at different percentages and types of fine aggregate substitutes.

In order to determine whether the types of aggregate substitutes, percentages of aggregate substitutes, and their interaction have any significant effects on the ($\underline{f'_c}$) values of the new cementitious concrete composites, a two-way ANOVA was used. Complete details of the mathematical procedure using this method to solve for the current problem is well demonstrated by Howell (1992). The results of applying this method to the $\underline{f'_c}$ problem case are summarized in Table 16. These results reveal that at .05 level of significant, there were significant effects for the percentages and types of aggregate substitutes as well as their interaction on the ($\underline{f'_c}$) of the new cementitious concrete composites. This is simply because the tabulated critical values of ($\underline{F}$) were as follows:

$$\underline{F}_{\%}\ (3,48) = 2.80 < [F_c = 8.21]$$

$$\underline{F}_{T}\ (2,48) = 3.19 < [F_c = 10.50]$$

$$\underline{F}_{\%\text{-}T}\ (6,48) = 2.30 < [F_c = 8.11]$$

It is to be noted that the significant interaction between the percentages and types of aggregate substitutes indicates that the effect of these percentages on the ($\underline{f'_c}$) values of the new concrete composites depend on the type of solid waste materials used and vice versa. For example, the ($\underline{f'_c}$) differences in the range of 5 and 20% aggregate substitutes for concrete composites containing plastics and fiberglass waste materials are larger than those differences on concrete composites containing glass waste material. Another view is that the ($\underline{f'_c}$) differences among the three types of aggregate substitutes are more extreme for 15 and 20% aggregate substitutes than they are for 5 and 10% aggregate substitutes. These observations can be seen from the values of ($\underline{f'_c}$) shown in Table 15.

Table 15

The Values of f'c and Number of Tested Specimens for The New Cementitious Concrete Composites Containing Different Aggregate Substitutes at Different Volume Percentages

Percentage of aggregate substitute	Type of fine aggregate substitute in new cementitious concrete composite and the average compressive strength (psi) and number of tested specimens			Total
	Plastics	Glass	Fiberglass	group
5%	4416 (5)	4300 (5)	4452 (5)	4389 (15)
10%	3864 (5)	4084 (5)	4016 (5)	3988 (15)
15%	3284 (5)	4046 (5)	3798 (5)	3709 (15)
20%	4090 (5)	5040 (5)	3204 (5)	4111 (15)
Total group	3914 (20)	4368 (20)	3868 (20)	

Table 16

Results Obtained From Two-Way ANOVA on Compressive Strength for The New Cementitious Concrete Composites

Source of Variation	df	SS	MS	Fc	p
% of aggregate (%)	3	3582085	1194028	8.21	0.0005
Type of aggregate (T)	2	3054880	1527440	10.50	0.0005
Interaction (%-T)	6	7076320	1179387	8.11	0.0005
Error	48	6980400	145425		

It is to be remembered that the use of Two-Way ANOVA has assisted to conclude that there were significant effects for the percentages and types of aggregate substitutes as well as their interaction on the compressive strength of the new cementitious concrete composites. However, in order to determine whether there were significant differences among the average values of (f'_c) of the new cementitious concrete composites (containing different types of aggregate substitutes at different percentages) and that value for the control concrete composite, the researcher used One-Way ANOVA method. In addition, the Tukey HSD procedure was used to identify any significant differences among the different concrete composites at each percentage of aggregate substitutes. These methods were applied to four sets of data individually. Each one of these sets included three new cementitious concrete composites (either at 5, 10, 15, or 20% aggregate substitutes) and the (f'_c) values of the five tested specimens of the control concrete composite. The following sections discuss the obtained results in details for each set.

Five-percent aggregate substitute. Results generated by applying One-Way ANOVA to the (f'_c) for the control and new concrete composites containing 5% aggregate substitutes are summarized in Table 17. Step-by-step procedure to show how the results shown in Table 17 were obtained is described by Howell (1992). These results reveal that at .05 level of significant, there were significant differences between the (f'_c) value of the control concrete composite and those values for the new concrete composites containing 5% aggregate substitutes. This is simply because that the tabulated critical value of (F) was as follows:

$$F\,(3,16) = 3.24 < [F_c = 5.03]$$

On the other hand, Tukey HSD procedure was used to identify any significant differences among the control and new concrete composites containing 5% aggregate substitutes. Final results shown in Table 18 (see Appendix I1 for more detail) indicate that the (f'_c) value of the control concrete composite is different from (i.e. higher and better than) those for the new concrete composites containing 5% aggregate substitutes. It can also be noticed that no significant differences can be identified among the three new concrete composites containing 5% aggregate substitutes. This simply means that all these new concrete composites have almost the same (f'_c) values at 5% aggregate substitute.

Table 17

Results Obtained From One-Way ANOVA on Compressive Strength for The Control and New Cementitious Concrete Composites Containing 5% Aggregate Substitutes

Source of Variation	df	SS	MS	F_c	p
Treatment	3	3409575	1136525	05.03	< .025
Error	16	3615720	225983		

Table 18

Final Results Obtained From Tukey HSD Procedure on f'c for The Control and New Cementitious Concrete Composites Containing 5% Aggregate Substitutes

Composite	Glass 5%	Plastics 5%	Fiberglass 5%	Control
f'_c (psi)	4300	4416	4452	5334

Ten-percent aggregate substitute. The same procedures of One-Way ANOVA and Tukey HSD were used to determine and identify any significant differences between the value of the (f'_c) of the control concrete composite and those values for the new concrete composites containing 10% aggregate substitutes. Results of the one-way ANOVA for the (f'_c) problem case are summarized in Table 19. Again, the results shown in this Table reveal that at .05 level of significant, there were significant differences among the (f'_c) values of the control and new concrete composites containing 10% aggregate substitutes. This is simply due to the fact that the tabulated critical value of (F) was as follows:

Table 19

Results Obtained From One-Way ANOVA on Compressive Strength for The Control and New Cementitious Concrete Composites Containing 10% Aggregate Substitutes

Source of Variation	df	SS	MS	F_c	p
Treatment	3	6920815	2306938	14.47	< .01
Error	16	2551680	159480		

$$F(3,16) = 3.24 < [F_c = 14.47]$$

On the other hand, results obtained from the application of Tukey HSD procedure to the same set of data are shown in Table 20 (see Appendix 12 for more detail).

Table 20

Results Obtained From Tukey HSD Procedure on Compressive Strength for The Control and New Cementitious Concrete Composites Containing 10% Aggregate Substitutes

Composite	Plastics 10%	Fiberglass 10%	Glass 10%	Control
f'_c (psi)	3864	4016	4084	5334

The results shown above reveal that the (f'_c) of the control concrete composite is higher and better than those strengths for the new concrete composites containing 10% aggregate substitutes. The table shows also that no significant differences can be identified among the three new concrete composites at the same percentage. This simply means that at 10% aggregate substitute, the three new concrete composites have almost the same (f'_c) values. This conclusion is similar to that obtained in the case of 5% aggregate substitutes.

Fifteen-percent aggregate substitute. Results obtained from applying One-Way ANOVA to the (f'_c) problem case at 15% aggregate substitutes are summarized in Table 21.

Table 21

Results Obtained From One-Way ANOVA on Compressive Strength for The Control and New Cementitious Concrete Composites Containing 15% Aggregate Substitutes

Source of Variation	df	SS	MS	F_c	p
Treatment	3	11408855	3802952	19.17	< .01
Error	16	3174840	198428		

Again, the obtained results shown in table 21 indicate that at .05 level of significant, there were significant differences among the values of the (f'_c) of the control and new concrete composites containing 15% aggregate substitutes. This is because that the tabulated critical value of F was as follows:

$$F\ (3.16) = 3.24 < [F_c = 19.17]$$

On the other hand, Tukey HSD procedure was used to identify any significant differences among the control and new concrete composites containing the same percentage of aggregate substitutes. Final results are shown in Table 22 and Appendix I3.

Table 22

Results Obtained From Tukey HSD Procedure on Compressive Strength for The Control and New Cementitious Concrete Composites Containing 15% Aggregate Substitutes

Composite	Plastics 15%	Fiberglass 15%	Glass 15%	Control
f'_c (psi)	3284	3798	4046	5334

The obtained results shown above denote that the ($\underline{f'_c}$) value of the control concrete composite is higher and better than those strengths for the new concrete composites containing 15% aggregate substitutes. It can also be noticed that no significant differences can be identified among the new concrete composites containing 15% aggregate substitutes (plastics, fiberglass, and glass). This simply means that all these new concrete composites have almost the same ($\underline{f'_c}$) at 15% aggregate substitute. This conclusion is similar to those obtained in the 5% and 10% aggregate substitutes cases.

Twenty-percent aggregate substitute. Results obtained from applying One-Way ANOVA to the fourth set of ($\underline{f'_c}$) values for the control and new cementitious concrete composites containing 20% aggregate substitutes are summarized in Table 23. These results prove that at .05 level of significant, there were significant differences among the ($\underline{f'_c}$) values of the control concrete composite and those values for the new concrete composites containing 20% aggregate substitutes. This is due to the fact that the tabulated critical value of $\underline{F}$ was as follows:

$$\underline{F}\ (3.16) = 3.24 < [F_c = 24.54]$$

Table 23

Results Obtained From One-Way ANOVA on Compressive Strength for The Control and New Cementitious Concrete Composites Containing 20% Aggregate Substitutes

Source of Variation	df	SS	MS	Fc	p
Treatment	3	14036580	4678860	24.54	< .01
Error	16	3050640	190665		

When Tukey HSD procedure was used to identify any significant differences among the control and new concrete composites containing 20% aggregate substitutes, the following results were shown (Table 24, see also Appendix I4 for more detail).

Table 24

Results Obtained From Tukey HSD Procedure on Compressive Strength for The Control and New Cementitious Concrete Composites Containing 20% Aggregate Substitutes

Composite	Fiberglass 20%	Plastics 20%	Glass 20%	Control
f'_c (psi)	3204	4090	5040	5334

The obtained results shown above indicate that the f'_c values of the control concrete composite and new concrete composite containing 20% glass aggregate substitute are higher and better than those f'_c for the new concrete composites containing 20% fiberglass and plastics substitutes. It can also be noticed that no significant differences can be identified between the control and glass concrete composites. On the other hand, the table shows that a significant difference has been identified between the fiberglass and plastics concrete composites. This simply means that the new concrete composite containing plastics aggregate is better than that containing fiberglass in terms of their (f'_c) values.

Graphical representation and analysis. Graphical representation for the obtained (f'_c) values for all the cementitious concrete composites tested in this study is shown in Figure 9. The X-axis in this figure represents the percentage of aggregate substitute existed in each concrete composite while the Y-axis represents the average (f'_c) for these composites. It is to be noticed that the (f'_c) for the control concrete composite is represented by a straight line parallel to the X-axis. The figure also shows the best curve fitting for each category of the new concrete composites containing one of the three waste materials used in this research (plastics, glass, and fiberglass).

As can be seen from Figure 9, the best curve fittings for the new concrete composites containing plastics and glass substitutes are polynomial curves of the second degree. On the other hand, a power curve represents the trend of the (f'_c) for the fiberglass concrete composites. Equations 21 through 23 demonstrate the relationships between the compressive strength ($\underline{f'_c}$) and the percentage of aggregate substitutes (p) for the different concrete composites containing plastics, glass, and fiberglass waste materials respectively.

$$\underline{f'_c} = 6071.5 - 373.9\,(p_P) + 13.7\,(p_P)^2 \qquad \text{(psi)} \qquad (21)$$

$$\underline{f'_c} = 5332.5 - 258.7\,(p_G) + 12.1\,(p_G)^2 \qquad \text{(psi)} \qquad (22)$$

$$\underline{f'_c} = 6435.88\,(p_{FG})^{-0.214773} \qquad \text{(psi)} \qquad (23)$$

It is to be mentioned that the values of (p) in equations 21 through 23 range from 5 to 20 only (i.e. no higher percentages are considered in these equations). Figure 9 shows clearly that the ($\underline{f'_c}$) value of the control concrete composite has been drastically and continuously reduced by adding more volume percentage of the fiberglass waste material aggregates. This decline in $\underline{f'_c}$ ranged from about 15% (in case of 5% fiberglass aggregate) to 37% (in case of 20% fiberglass aggregate). The Figure also shows that the average ($\underline{f'_c}$) of the control composite has been continuously reduced by adding more plastics waste material up to about 14% where the ($\underline{f'_c}$) of this new concrete composite started to increase. However, the ($\underline{f'_c}$) value at 20% plastics aggregate was still a way below the actual ($\underline{f'_c}$) of the control composite (about 24%). The plastics curve shows also that the reduction in $\underline{f'_c}$ ranged from about 15% (in case of 5% plastics aggregate) to 36% (in case of 14% plastics aggregate). This range is almost the same as that for fiberglass concrete composites.

Figure 9 further shows that in case of adding glass waste aggregate substitutes, the behavior of these concrete composites resembles that with plastics aggregate substitute to some extent. The glass curve shows that the value of ($\underline{f'_c}$) for this concrete composite went down only in the region from 5 to about 10% glass aggregate substitute. However, the concrete composite gained more strength when more than 10% glass aggregate substitute was added and up to 20% of this aggregate. Furthermore, the glass curve shows also that the reduction in the ($\underline{f'_c}$) of the control concrete composite ranged from about 6% (in case of containing 20% glass aggregate) to 27% (in case of about 10% glass aggregate). Of course, this range is lower than that for fiberglass and plastics concrete composites

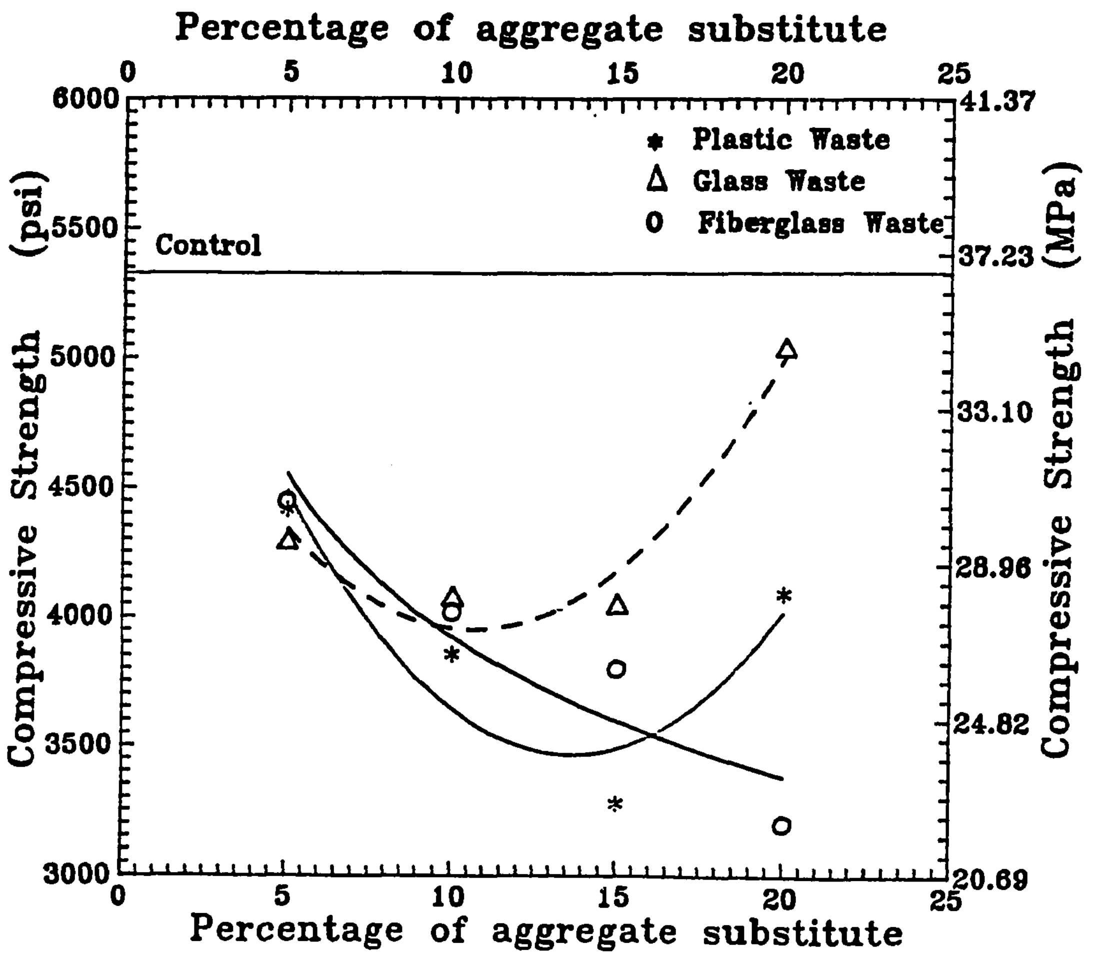


Figure 9. The compressive strength (f'_c) versus the percentage of aggregate substitutes in the new cementitious concrete composites.

In general, Figure 9 reveals that all the values of (f'_c) of the new cementitious concrete composites containing waste aggregate materials are below the actual obtained value for the control concrete composite (by at least 15%). An exception to this conclusion was the case of adding 20% glass aggregate substitute where the value of (f'_c) for this concrete composite was slightly below that for the control one. This means that no significant differences can be identified between these two composites. However, there are obvious differences between the (f'_c) values for these composites and those for the new concrete composites containing plastics or fiberglass at the same percentage (20%). The figure also shows that at 5 and 10% aggregate substitutes, the three types of new concrete composites (containing plastics, glass, and fiberglass) have close (f'_c) values. This means that no significant differences can be identified among these composites. All these observations match those obtained through the statistical analyses of these data. However, at 15% aggregate substitutes, Figure 9 shows that there is a significant difference between the glass concrete composite and both the plastics and fiberglass ones. In addition, the Figure shows that the (f'_c) for both plastics and fiberglass concrete composites are almost the same. This observation contradicts the results obtained from the statistical analysis of these data where no significant differences among the three composites were concluded.

Splitting Tensile Strength

The values of the calculated splitting tensile strength (T) for all the tested specimens of the twelve developed concrete composites were used for the statistical analysis part in this research study. SPSS computer software package was used to analyze these obtained data. These data were prepared as a two-way factor using the percentage and type of aggregate substitute as a two-way analysis of variance (Two-Way ANOVA) method. Appendix F shows a list of the arrangement of these data. Table 25 shows the average statistical values of (T) for each new concrete composite at different percentages and the number of tested specimens. It is to be noted again that these values are not rounded as those shown in Table 10 (which are in accordance with ASTM standard, 1991c) because of the nature of the statistical treatment. Table 25 shows also the average values of (T) for the total groups at different percentages and types of aggregate substitutes.

In order to determine whether the types and percentages of aggregate substitutes as well as their interaction have any significant effects on the T values of the new cementitious concrete composites, a two-way ANOVA was used. The results, which are summarized in Table 26, indicate that at .05 level of significant, there were only significant effects for the types of aggregate substitutes on the (T) values of these composites. On the other hand, there were no significant effects for the percentages of aggregate substitutes and their interaction with the types of these aggregates on the T values of the new concrete composites. This is simply because the tabulated critical values of (F) were as follows:

$$F_{\%}\ (3,60) = 2.76 > [F_c = 0.712]$$

$$F_T\ (2,60) = 3.15 < [F_c = 6.553]$$

$$F_{\%\text{-}T}\ (6,60) = 2.25 > [F_c = 0.988]$$

It is to be noted that the failure of having significant interaction between the types and percentages of the used aggregates substitutes on the values of (T) for the new concrete composites means that the effect of the types of aggregate substitutes does not depend on the percentages of solid waste material used. For example, there were no significant differences in the (T) values for the total group (last column in Table 25) among concrete composites containing 5, 10, 15, and 20% aggregate substitutes. On the other hand, significant differences in the (T) values for the total group (last row in the Table) can be seen among different types of concrete composites.

Again, One-Way ANOVA was used to examine any significant differences among the average (T) values of the control and new concrete composites (containing different types of aggregate substitutes at different percentages). Furthermore, Tukey HSD procedure was used to identify any significant differences among the different concrete composites at each percentage of aggregate substitutes. These methods were applied to four sets of data individually. Each one of the data sets included the (T) values of the six tested specimens of the control and three new concrete composites (either at 5, 10, 15, or 20% aggregate substitutes). The following sections discuss the obtained results in details for each set.

Table 25

The Values of (T) and Number of Tested Specimens for The New Cementitious Concrete Composites Containing Different Aggregate Substitutes at Different Volume Percentages

Percentage of aggregate substitute	Type of fine aggregate substitute in new cementitious concrete composite and the average splitting tensile strength (psi) and number of tested specimens			Total
	Plastics	Glass	Fiberglass	group
5%	6 438	6 495	6 495	18 476
10%	65 428	6 481	6 501	18 470
15%	6 448	6 434	6 478	18 453
20%	6 438	6 487	6 468	18 464
Total group	24 438	24 474	24 486	

Table 26

Results Obtained From Two-Way ANOVA on Splitting Tensile Strength for The New Cementitious Concrete Composites

Source of Variation	df	SS	MS	Fc	p
% of aggregate (%)	3	4975	1658	0.712	0.549
Type of aggregate (T)	2	30533	15267	6.553	0.003
Interaction (%-T)	6	13817	2303	0.988	0.441
Error	60	139775	2330		

Five-percent aggregate substitute. The results of applying One-Way ANOVA to the (T) values for the control and new concrete composites containing 5% aggregate substitutes are summarized in Table 27. These results reveal that at .05 significant level, there were significant differences among the (T) values of the control and new concrete composites containing 5% aggregate substitutes. This is because that the tabulated critical (F) value was as follows:

$$F\ (3,20) = 3.10 < [F_c = 3.54]$$

Table 27

Results Obtained From One-Way ANOVA on (T) for The Control and New Cementitious Concrete Composites Containing 5% Aggregate Substitutes

Source of Variation	df	SS	MS	Fc	p
Treatment	3	47678	15893	03.54	< .05
Error	20	89721	4486		

On the other hand, the final results obtained through the application of Tukey HSD procedure to the same set of data are shown in Table 28 and Appendix I5.

Table 28

Results Obtained From Tukey HSD Procedure on (T) for The Control and New Cementitious Concrete Composites Containing 5% Aggregate Substitutes

Composite	Plastics 5%	Glass 5%	Fiberglass 5%	Control
T (psi)	438	495	495	563

The obtained results shown above indicate that the (T) value of the control concrete composite is different from (i.e. higher and better than) this value for the 5% plastics concrete composite. It can also be noticed that no significant differences can be identified between the (T) values for the new concrete composites containing 5% glass and fiberglass aggregate substitutes and that value for either the control or plastics concrete composite.

Ten-percent aggregate substitute. The same procedures of One-Way ANOVA and Tukey HSD were used to determine and identify any significant differences among the (T) values for the control and new concrete composites containing 10% aggregate substitutes. Results of the One-Way ANOVA for the (T) problem case, which are summarized in Table 29 show that at .05 level of significant, there were significant differences between the (T) value of the control concrete composite and those values for the new concrete composites containing 10% aggregate substitutes. This is simply due to the fact that the tabulated critical value of (F) was as follows:

$$F\ (3,20) = 3.10 < [F_c = 08.02]$$

Table 29

Results Obtained From One-Way ANOVA on (T) for The Control and New Cementitious Concrete Composites Containing 10% Aggregate Substitutes

Source of Variation	df	SS	MS	Fc	p
Treatment	3	56758	18919	08.02	< .01
Error	20	47175	2359		

On the other hand, results obtained from the application of Tukey HSD procedure to the same set of data are shown in Table 30 (see also appendix I6 for more detail).

Table 30

Results Obtained From Tukey HSD Procedure on (T) for The Control and New Cementitious Concrete Composites Containing 10% Aggregate Substitutes

Composite	Plastics 10%	Glass 10%	Fiberglass 10%	Control
T (psi)	428	481	502	563

The above results indicate that the (T) value of the control concrete composite is higher and better than those for the new plastics and glass concrete composites. On the other hand, no significant differences were identified between the (T) values of the new fiberglass and control concrete composites. No significant differences were also identified among the (T) values of the three tested types of new concrete composites containing this percentage of aggregate substitute.

Fifteen-percent aggregate substitute. The results of the One-Way ANOVA for the (T) problem case at 15% aggregate substitute are summarized in Table 31. These results reveal that at .05 level of significant, there were significant differences among the average (T) values of the control and new concrete composites containing 15% aggregate substitutes. This is because that the tabulated critical value of F was as follows:

Table 31

Results Obtained From One-Way ANOVA on (T) for The Control and New Cementitious Concrete Composites Containing 15% Aggregate Substitutes

Source of Variation	df	SS	MS	F_c	p
Treatment	3	60608	20203	07.38	< .01
Error	20	54725	2736		

$$F\ (3.20) = 3.10 < [F_c = 07.38]$$

On the other hand, Tukey HSD procedure was used to identify any significant differences among the control and new concrete composites containing 15% aggregate substitutes. Final results shown in Table 32 and Appendix 17 indicate that the (T) value of the control concrete composite is significantly different from those values for the concrete composites containing 15% glass and plastics aggregates. However, no significant differences were identified between the T values of the new fiberglass and control concrete composites. It can also be noticed that no significant differences can be identified among the new concrete composites containing 15% aggregate substitutes (plastics, fiberglass, and glass). This conclusion is similar to this obtained in the 10% aggregate substitutes case.

Table 32

Results Obtained from Tukey HSD Procedure on (T) for The Control and New Cementitious Concrete Composites Containing 15% Aggregate Substitutes

Composite	Glass 15%	Plastics 15%	Fiberglass 15%	Control
T (psi)	434	448	478	563

Twenty-percent aggregate substitute. The results of applying One-Way ANOVA to the (T) values for the control and new concrete composites containing 20% aggregate substitutes are summarized in Table 33. The results in this Table show that at .05 level of significant, there were significant differences among the (T) values of the control and new concrete composites containing 20% aggregate substitutes. This is because the tabulated critical value of F was as follows:

$$F\ (3,20) = 3.10 < [F_c = 06.82]$$

On the other hand, results obtained from the application of Tukey HSD procedure to the same set of data are shown in Table 34 (see appendix 18 for more detail).

Table 33

Results Obtained from One-Way ANOVA on (T) for The Control and New Cementitious Concrete Composites Containing 20% Aggregate Substitutes

Source of Variation	df	SS	MS	Fc	p
Treatment	3	51661	17220	06.82	< .01
Error	20	50488	2524		

Table 34

Results Obtained from Tukey HSD Procedure on (T) for The Control and New Cementitious Concrete Composites Containing 20% Aggregate Substitutes

Composite	Plastics 20%	Fiberglass 20%	Glass 20%	Control
T (psi)	438	468	487	563

The obtained results shown above indicate that the (T) value of the control concrete composite is higher and better than those values for the new plastics and fiberglass concrete composites. On the other hand, no significant differences can be identified between the (T) values for the new glass and control composites. No significant differences can be also identified among all the new composites containing 20% aggregate substitutes. This conclusion is similar to those obtained in the 10% and 15% aggregate substitutes cases.

Graphical representation and analysis. The graphical representation for the obtained (T) values for all the cementitious concrete composites tested in this study is shown in Figure 10. In this figure, the X-axis represents the percentage of aggregate substitute existed in each concrete composite while the Y-axis represents the average (T) values for these composites. It is to be noticed that the (T) value for the control concrete composites is represented by a straight line parallel to the X-axis. The Figure also shows the best curve fitting for each category of the new concrete composite containing one of the three waste materials used in this research.

As can be seen from Figure 10, there is a linear relationship between the ($\underline{T}$) value and the percentage of aggregate substitute for both the plastics and fiberglass concrete composites. On the other hand, a polynomial curve of the second degree represents the trend of the ($\underline{T}$) values for the glass concrete composites. Equations 24 through 26 exhibit the relationships between the splitting tensile strength ($\underline{T}$) and the percentage of aggregate substitute (p) for the three different concrete composites containing plastics, glass, and fiberglass waste materials respectively.

$$\underline{T} = 435 + 0.4\,(p_P) \qquad \text{(psi)} \qquad (24)$$

$$\underline{T} = 573.75 - 17.75\,(p_G) + 0.65\,(p_G)^2 \qquad \text{(psi)} \qquad (25)$$

$$\underline{T} = 510 - 1.9\,(p_{FG}) \qquad \text{(psi)} \qquad (26)$$

Again, p values range from 5 to 20 only. Figure 10 shows clearly that the ($\underline{T}$) value of the control concrete composite has been continuously reduced by using more fiberglass aggregate substitute. This decrease in the ($\underline{T}$) value ranged from about 11% to 16% (at 5 and 20% fiberglass aggregate respectively). The Figure also shows that there is no noticeable differences among all the ($\underline{T}$) values for the new fiberglass concrete composites.

The average ($\underline{T}$) values of all the concrete composites containing plastics substitutes (shown in Figure 10) are almost the same. Furthermore, all these values (between about 437 and 443 psi) are way below that of the control concrete composite. This decline in the ($\underline{T}$) values ranged from about 22% to 23% (at 20 and 5% plastics aggregate respectively). This decrease range is a little higher than that calculated for fiberglass concrete composites.

Figure 10 also shows that the behavior of the concrete composites containing glass substitutes does not resemble that of either plastics or fiberglass concrete composites. The glass curve shows that the ($\underline{T}$) value of this concrete composite went down only in the region between 5 and about 15% glass aggregate substitute. However, the concrete composite gained more strength when the glass aggregate substitute was increased to 20%.

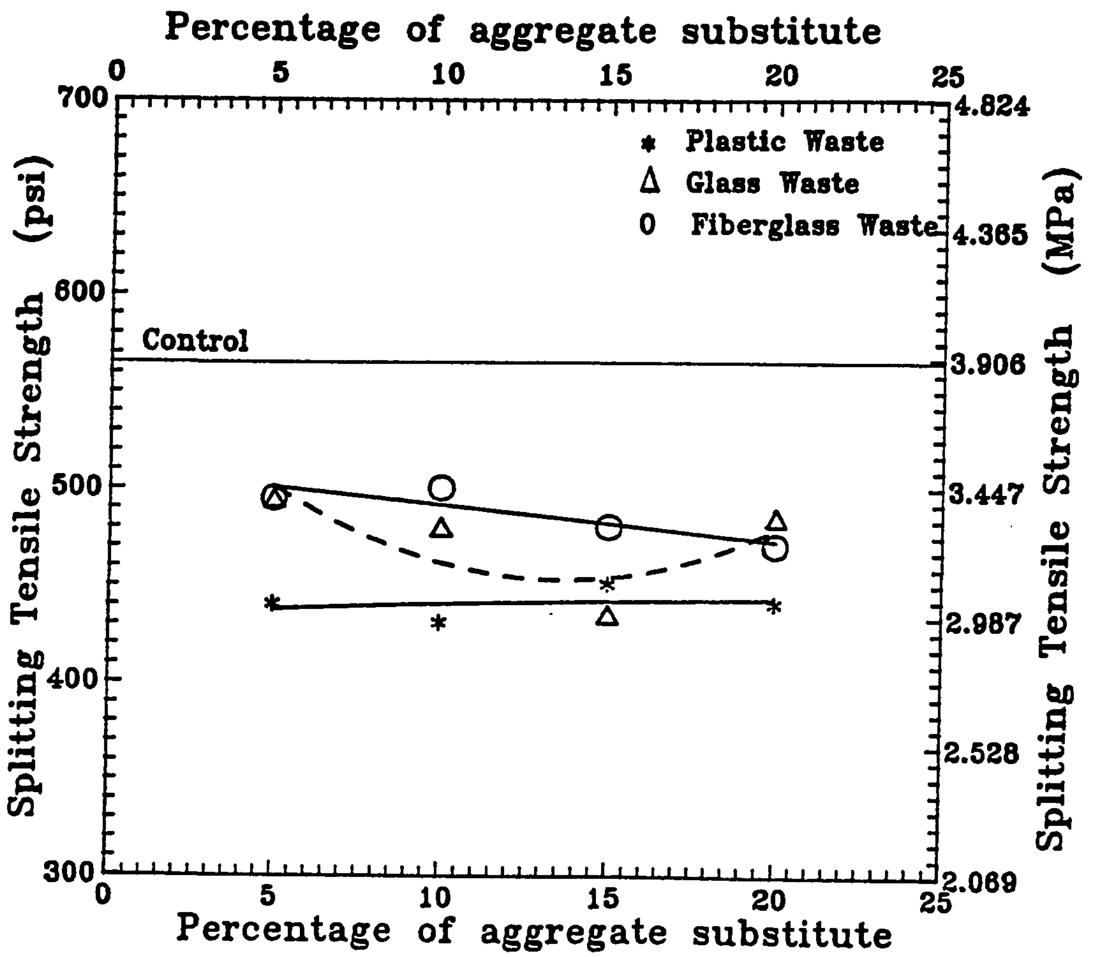


Figure 10. The splitting tensile strength (T) versus the percentage of aggregate substitutes in the new cementitious concrete composites.

Furthermore, the glass curve shows also that the reduction in the (T) value of the control concrete composite ranged from about 11% (at 5% glass aggregate) to 20% (at 15% glass aggregate). Figure 10 shows also that the (T) values (or the behavior) of the glass concrete composite lay in between those of plastics and fiberglass concrete composites.

In general, Figure 10 reveals that all the (T) values of the new cementitious concrete composites containing waste aggregate materials are within a range between 437 and 501 psi (estimated values of (T) obtained through the use of equations 24-26). This means that there is no significant difference in the (T) values among these concrete composites based on their percentages of aggregate substitutes used. However, the Figure clearly shows that the (T) values of the concrete composites containing fiberglass substitutes are better than those containing glass and plastics substitutes. Indeed, all these (T) values are founded to be below the actual obtained value for the control concrete composite by at least 11%. The Figure also shows that the (T) values of all the tested fiberglass concrete composites and glass concrete composites at 5 and 20% aggregate substitutes are the closest values to that of control concrete composite. This means that no significant differences can be identified between these composites and the control one. This conclusion matches that obtained through the statistical analysis with the exception that the graphical analysis shows no significant difference between the (T) value of the control concrete composite and that (T) value for the concrete composite containing 20% fiberglass aggregate substitute. However, there are obvious differences between the (T) values of all the plastics concrete composites and glass concrete composites at 10 and 15% aggregate substitutes and that of control concrete composite. This means that significant differences can be identified among these composites and the control one. All these observations match those obtained through the statistical analyses of these data.

Modulus of Rupture

Again, the values of the calculated modulus of rupture (R) for the tested specimens of all the new concrete composites were used for the statistical analysis part in this study. These data were prepared (shown in Appendix G) for a Two-Way ANOVA. Table 35 shows the average values of (R) for each new concrete composite at different percentages and the number of tested specimens. It is to be noted here that these values are not rounded as those shown in Table 12 (which are in accordance with ASTM standard, 1991d) because of the nature of the statistical treatment. Table 35 also shows the average values of (R) for the total groups at different percentages and type of fine aggregate substitutes.

A two-way ANOVA method was used to examine significant effects of the types and percentages of aggregate substitutes and their interaction on the (R) values of the new cementitious concrete composites. The obtained results from this method are summarized in Table 36. These results reveal that at .05 level of significant, there were significant effects for the types and percentages of aggregate substitutes and their interaction on the (R) values of the new cementitious concrete composites. This is simply because the tabulated critical values of F were as follows:

$$F_{\%}\ (3,48) = 2.80 < [F_c = 18.89]$$

$$F_{T}\ (2,48) = 3.19 < [F_c = 23.23]$$

$$F_{\%\text{-}T}\ (6.48) = 2.30 < [F_c = 07.47]$$

The obtained results from the statistical analysis shows that there is a significant interaction between the percentages and types of the used aggregates substitutes on the (R) values of the new concrete composites. This means that the effect of the percentages of aggregate substitutes depends on the type of solid waste material used and vice versa. For example, there were significant differences in the R values of the total group (last column in Table 35) among concrete composites containing 5, 10, 15, and 20% aggregate substitutes.

Once more, One-Way ANOVA method was used to determine whether there were significant differences among the (R) values of the control and new concrete composites. Then, the Tukey HSD procedure was used to identify any significant differences among the tested concrete composites at each percentage of aggregate substitutes. These two methods were applied to four sets of data individually. The following sections discuss the obtained results in details for each set.

Table 35

The Values of (R) and Number of Tested Specimens for The New Cementitious Concrete Composites Containing Different Aggregate Substitutes at Different Volume Percentages

Percentage of aggregate substitute	Type of fine aggregate substitute in new cementitious concrete composite and the average modulus of rupture (psi) and number of tested specimens			Total
	Plastics	Glass	Fiberglass	group
5%	944 5	909 5	819 5	891 15
10%	801 5	874 5	805 5	827 15
15%	650 5	822 5	744 5	739 15
20%	635 5	912 5	762 5	770 15
Total group	758 20	879 20	783 20	

Table 36

Results Obtained From Two-Way ANOVA on Modulus of Rupture for The New Cementitious Concrete Composites

Source of Variation	df	SS	MS	Fc	p
% of aggregate (%)	3	201731	67244	18.89	0.0005
Type of aggregate (T)	2	165391	82695	23.23	0.0005
Interaction (%-T)	6	159473	26579	07.47	0.0005
Error	48	170860	3560		

Five-percent aggregate substitute. Results obtained from applying one-way ANOVA to the (R) values for the control and new concrete composites containing 5% aggregate substitutes are shown in Table 37. These results reveal that at .05 significant level, there were no significant differences among the (R) values of the control concrete composite and those values for the new concrete composites containing 5% aggregate substitutes. This is simply because that the tabulated critical value of (F) was as follows:

$$F\ (3,16) = 3.24 > [F_c = 2.67]$$

Tukey HSD procedure was then used to enhance the results obtained from using one-way ANOVA and make sure that significant differences can not be identified among the control and new concrete composites containing 5% aggregate substitutes. Final results are shown in Table 38 and Appendix I9. The results shown in this Table indicate that the (R) value of the control concrete composite is not different from those for the new concrete composites containing 5% aggregate substitute. That means that no significant differences can be identified among the (R) values of the control and new concrete composites containing 5% aggregate substitutes.

Table 37

Results Obtained From One-Way ANOVA on (R) for The Control and New Cementitious Concrete Composites Containing 5% Aggregate Substitutes

Source of Variation	df	SS	MS	F_c	p
Treatment	3	42185	14062	02.67	> .05
Error	16	84390	5274		

Table 38

Results Obtained From Tukey HSD Procedure on (R) for The Control and New Cementitious Concrete Composites Containing 5% Aggregate Substitutes

Composite	Fiberglass 5%	Control	Glass 5%	Plastics 5%
R (psi)	819	878	909	944

Ten-percent aggregate substitute. The same procedures of one-way ANOVA and Tukey HSD were used to determine and identify any significant differences among the (R) values of the control and new concrete composites containing 10% aggregate substitutes. Results of the one-way ANOVA for the (R) problem at this percentage are summarized in Table 39. The obtained results shown in this Table reveal that at .05 level of significant, there were significant differences between the (R) value of the control concrete composite and those values for the new concrete composites containing 10% aggregate substitutes. This is simply due to the fact that the tabulated critical value of F was as follows:

$$F\,(3,16) = 3.24 < [F_c = 03.67]$$

Table 39

Results Obtained From One-Way ANOVA on (R) for The Control and New Cementitious Concrete Composites Containing 10% Aggregate Substitutes

Source of Variation	df	SS	MS	F_c	p
Treatment	3	26725	8908	03.67	< .05
Error	16	38820	2426		

On the other hand, results obtained from the application of Tukey HSD procedure to the same set of data are shown in Table 40 (see also Appendix I10 for more detail). The obtained results shown in this Table indicate that no significant differences were identified among the (R) values of the control and new concrete composites containing 10% aggregate substitutes. This conclusion, which is similar to that obtained in the 5% aggregate substitutes case, contradicts with that conclusion obtained from the application of the one-way method to the same data as shown above. Same contradiction in results would appear if Newman-Keuls test was applied to the same data (Howell, 1992).

Fifteen-percent aggregate substitute. The results of the one-way ANOVA for the modulus of rupture problem case at 15% aggregate substitutes are summarized in Table 41.

Table 40

Results Obtained From Tukey HSD Procedure on (R) for The Control and New Cementitious Concrete Composites Containing 10% Aggregate Substitutes

Composite	Plastics 10%	Fiberglass 10%	Glass 10%	Control
R (psi)	801	805	874	878

Table 41

Results Obtained From One-Way ANOVA on (R) for The Control and New Cementitious Concrete Composites Containing 15% Aggregate Substitutes

Source of Variation	df	SS	MS	Fc	p
Treatment	3	146975	48992	27.19	< .01
Error	16	28830	1802		

The obtained results shown above suggest that at .05 level of significant, there were significant differences among the average ($\underline{R}$) values of the control and new concrete composites containing 15% aggregate substitutes. This is because that the tabulated critical $\underline{F}$ value was as follows:

$$\underline{F}\,(3,16) = 3.24 < [F_c = 27.19]$$

Once more, Tukey HSD procedure was used to identify any significant differences among the control and new concrete composites containing 15% aggregate substitutes. Final results shown in Table 42 and Appendix I11 indicate that significant differences were identified between the ($\underline{R}$) values of both the control and glass concrete composites and those values for the plastics and fiberglass concrete composites. significant difference was also detected between the new concrete composites containing 15% plastics and fiberglass aggregate substitutes. On the other hand, no significant difference was identified between the ($\underline{R}$) value of the new concrete composite containing 15% glass aggregate substitute and that value for the control concrete composite. This conclusion differs from those obtained in cases of 5 and 10% aggregate substitutes.

Twenty-percent aggregate substitute. The results of the one-way ANOVA for the modulus of rupture problem case at 20% aggregate substitutes are summarized in Table 43. This table shows that at .05 level of significant, there were significant differences between the ($\underline{R}$) value of the control concrete composite and those values for the new concrete composites containing 20% aggregate substitutes. This is simply due to the fact that the tabulated critical value of F was as follows:

$$\underline{F}\,(3,16) = 3.24 < [F_c = 26.40]$$

Table 42

Results Obtained From Tukey HSD Procedure on (R) for The Control and New Cementitious Concrete Composites Containing 15% Aggregate Substitutes

Composite	Plastics 15%	Fiberglass 15%	Glass 15%	Control
$\underline{R}$ (psi)	650	744	822	878

Table 43

Results Obtained From One-Way ANOVA on (R) for The Control and New Cementitious Concrete Composites Containing 20% Aggregate Substitutes

Source of Variation	df	SS	MS	Fc	p
Treatment	3	236274	78758	26.40	< .01
Error	16	47740	2984		

On the other hand, Tukey HSD procedure was used to identify any significant differences among the control and new concrete composites containing 20% aggregate substitutes. Final results shown in Table 44 and Appendix I12 indicate that the (R) values of the control and 20% glass concrete composites are higher and better than those values for the new concrete composites containing 20% plastics and fiberglass aggregate substitutes. It can also be noticed that a significant difference can be identified between the new concrete composites containing 20% plastics and fiberglass aggregate substitutes. On the other hand, no significant differences can be identified between the new concrete composite containing 20% glass aggregate substitute and the control concrete composite. This conclusion is similar to that obtained in the 15% aggregate substitutes case.

Table 44

Results Obtained From Tukey HSD Procedure on (R) for The Control and New Cementitious Concrete Composites Containing 20% Aggregate Substitutes

Composite	Plastics 20%	Fiberglass 20%	Control	Glass 20%
R (psi)	635	762	878	912

Graphical representation and analysis. The graphical representation for the obtained $\underline{R}$ values for all the tested cementitious concrete composites in this study is shown in Figure 11. The X-axis in this figure represents the percentage of aggregate substitute existed in each concrete composite while the Y-axis represents the average ($\underline{R}$) values for these composites. It is to be noticed that the ($\underline{R}$) value for the control concrete composite is represented by a straight line parallel to the X-axis. The Figure also shows the best curve fitting for each category of the new concrete composite containing one of the three waste materials used in this research.

Figure 11 shows that the relationships between the $\underline{R}$ values and percentages of aggregate substitutes for both plastics and fiberglass concrete composites can be represented as power curves. On the other hand, a polynomial curve of the second degree represents the trend of the average $\underline{R}$ values for the glass concrete composite within a range of 5 to 20% glass aggregate substitutes. Equations 27 through 29 layout the relationships between the modulus of rupture ($\underline{R}$) and the percentage of aggregate substitutes (p) for the three different concrete composites containing plastics, glass, and fiberglass waste materials respectively.

$$\underline{R} = 1561.07\ (p_P)^{-0.306381} \qquad \text{(psi)} \qquad (27)$$

$$\underline{R} = 1048.75 - 32.35\ (p_G) + 1.25\ (p_G)^2 \qquad \text{(psi)} \qquad (28)$$

$$\underline{R} = 917.77\ (p_{FG})^{-0.0666522} \qquad \text{(psi)} \qquad (29)$$

Once more, the values of p in the above equations range from 5 to 20 only. Figure 11 shows clearly that the ($\underline{R}$) value of the control concrete composite has been continuously reduced by adding more volume percentage of the fiberglass waste material aggregates. This reduction in ($\underline{R}$) values ranged from about 6% (at 5% fiberglass aggregate) to 15% (at 20% fiberglass aggregate). The Figure shows also that there are noticeable differences between the ($\underline{R}$) values for the fiberglass concrete composite at 5 and 10% aggregates and those values for the same concrete composite at 15 and 20% aggregate.

In case of the new concrete composites containing plastics aggregate, Figure 11 shows that the reduction rate of the average ($\underline{R}$) values of these composites in the range of 5 to 20% plastics aggregate substitute is higher than that for fiberglass concrete composites. These ($\underline{R}$) values ranged from about 8% above the ($\underline{R}$) value for the control concrete composite (at 5% plastics aggregate) to 29% below that value (at about 20% plastics aggregate). The Figure shows also that there are noticeable differences between the ($\underline{R}$) values for the new concrete composites containing 5 and 10% plastics aggregate and those values for the same concrete composites containing 15 and 20% plastics aggregate. This conclusion is same as that concluded for fiberglass concrete composites.

Figure 11 also shows that in the case of adding glass aggregate substitutes, the behavior of these concrete composites does not resemble that of either plastics or fiberglass aggregate substitutes. The glass curve shows that the ($\underline{R}$) value of this composite declined only in the region between 5 and about 13% glass aggregate substitute and then gained more flexure strength when the glass aggregate substitute was increased to 20%. In addition, the glass curve shows that the ($\underline{R}$) values ranged from about 4% above to 5% below that value for the control concrete composite (at 5 and about 13% glass aggregate respectively). This range indicates that the behavior of all the tested glass concrete composites is almost the same (within 5% above and below) as the control composite.

Based on the ($\underline{R}$) values depicted on Figure 11, the glass-containing concrete composites are the most consistent composites within the selected range of 5 and 20% aggregate substitutes followed by fiberglass and finally plastics concrete composites. It is very interesting to notice that three new concrete composites (containing 5 and 20% glass aggregate as well as 5% plastics aggregate) have higher ($\underline{R}$) than that of the control one. The Figure also shows that there are only four (out of twelve) tested concrete composites that have significant differences between their $\underline{R}$ values and that of the control one. These four composites are the 15 and 20% plastics and fiberglass concrete composites. All these observations match those obtained through the statistical analyses of these data. However, the Figure shows at 10% aggregate substitutes that all the ($\underline{R}$) values for the tested concrete composites are close to each other (i.e. within the experimental error). This suggests that all these composites have no significant differences between each other up to that percent. This observation matches the conclusion obtained from applying Tukey HSD procedure to

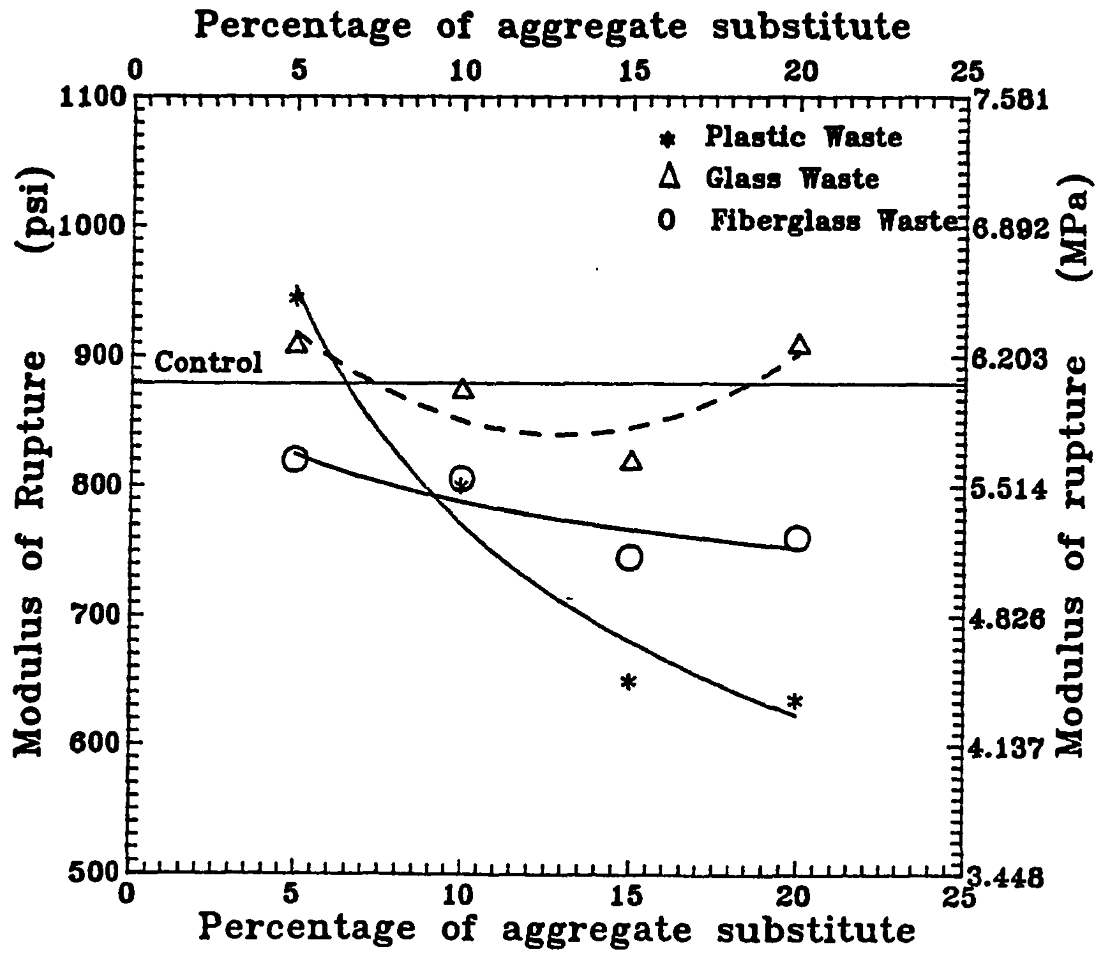


Figure 11. The modulus of rupture (R) versus the percentage of aggregate substitutes in the new cementitious concrete composites.

this set of data and contradicts the results obtained from the one-way ANOVA to the same set of data.

Flexural Modulus of Elasticity

The last property that the researcher has considered in this study was the flexural modulus of elasticity (E). Once again, the values of the calculated (E) for the tested specimens of all the new concrete composites were used as data base for the statistical analysis part in this research study. These data were prepared (as shown in Appendix H) as a two-way factor using the percentage and type of aggregate substitute as a two-way analysis of variance (Two-Way ANOVA) method. Table 45 shows the average statistical values of (E) for each new concrete composite at different percentages and the number of tested specimens. The Table shows also the average values of (E) for the total groups at different percentages and types of fine aggregate substitutes.

As was done before, a two-way ANOVA was used to determine whether the types of aggregate substitutes, percentages of aggregate substitutes, and their interaction have any significant effects on the (E) values of the new cementitious concrete composites. The results obtained from applying this method to the data base are summarized in Table 46. These results show that at .05 level of significant, there were significant effects for the types of aggregate substitutes and their interaction with the percentage of aggregate substitutes on the (E) values of the new cementitious concrete composites. On the other hand, there were no significant effects for the percentages of aggregate substitutes on the (E) values of the new cementitious concrete composites. This is simply because the tabulated critical F values were as follows:

$$F_{\%}\ (3{,}48) = 2.80 > [F_c = 0.885]$$

$$F_T\ (2{,}48) = 3.19 < [F_c = 03.23]$$

$$F_{\%\text{-}T}\ (6{,}48) = 2.30 < [F_c = 04.17]$$

Again, results obtained from the statistical analysis shows that there is a significant interaction between the types and percentages of the used aggregates substitutes on the (E) values of the new concrete composites. This means that the effect of the percentages of aggregate substitutes depends on the type of solid waste material used. For example, the (E) differences in the range of 5 and 20% aggregate substitutes for concrete composites containing plastics waste material are larger than those differences on concrete composites containing glass and fiberglass waste materials respectively. This observation can be seen from the values of (E) shown in Table 45.

Table 45

The Values of (E) and Number of Tested Specimens for The New Cementitious Concrete Composites Containing Different Aggregate Substitutes at Different Volume Percentages

Percentage of aggregate substitute	Type of fine aggregate substitute in new cementitious concrete composite and the average modulus of elasticity (Ksi) and number of tested specimens			Total
	Plastics	Glass	Fiberglass	group
5%	5 99.40	5 71.65	5 81.60	15 84.22
10%	5 70.65	5 62.54	5 90.93	15 74.71
15%	5 62.35	5 82.19	5 90.26	15 78.27
20%	5 61.82	5 90.57	5 81.81	15 78.07
Total group	20 73.56	20 76.74	20 86.15	

One-way ANOVA and Tukey HSD procedures were then used to determine and identify any significant differences among the (E) values of all the control and new concrete composites. These two methods were applied to the four sets of data individually as was done before. Each one of these data sets included three new cementitious concrete composites (either at 5, 10, 15, or 20% aggregate substitutes) and the (E) values of the five tested specimens of the control concrete composite. The following sections discuss the obtained results in details for each set.

Table 46

Results Obtained From Two-Way ANOVA on (E) Values for The New Cementitious Concrete Composites

Source of Variation	df	SS	MS	Fc	p
% of aggregate (%)	3	703.739	234.580	0.885	0.456
Type of aggregate (T)	2	1715.152	857.576	3.234	0.048
Interaction (%-T)	6	6632.430	1105.405	4.169	0.002
Error	48	12727.869	265.164		

Five-percent aggregate substitute. Results obtained from applying one-way ANOVA to the (E) values for the control and new concrete composites containing 5% aggregate substitutes are shown in Table 47.

Table 47

Results Obtained From One-Way ANOVA on (E) for The Control and New Cementitious Concrete Composites Containing 5% Aggregate Substitutes

Source of Variation	df	SS	MS	Fc	p
Treatment	3	3048.71	116.24	02.69	> .05
Error	16	6037.94	377.37		

The above results reveal that at .05 level of significant, there were no significant differences among the ($\underline{E}$) values of the control concrete composite and those values for the new concrete composites containing 5% aggregate substitutes. This is simply because that the tabulated critical value of ($\underline{F}$) was as follows:

$$\underline{F}\ (3,16) = 3.24 > [F_c = 2.69]$$

Tukey HSD procedure was used to enhance the results obtained above and make sure that significant differences can not be identified among the ($\underline{E}$) values for the control and new concrete composites containing 5% aggregate substitutes. Final results shown in Table 48 and Appendix I13 indicate that the ($\underline{E}$) value of the control concrete composite is not different from those for the new concrete composites containing 5% aggregate substitute. This means that no significant differences can be identified among the ($\underline{E}$) values of all the control and new concrete composites containing 5% aggregate substitutes.

<u>Ten-percent aggregate substitute</u>. The same procedures of one-way ANOVA and Tukey HSD were used to determine and identify any significant differences among the ($\underline{E}$) values of the control and new concrete composites containing 10% aggregate substitutes. Results of the one-way ANOVA for the ($\underline{E}$) problem case are summarized in Table 49. The obtained results shown in this Table reveal that at .05 level of significant, there were significant differences between the ($\underline{E}$) value of the control concrete composite and those values for the new concrete composites containing 10% aggregate substitutes. This is simply due to the fact that the tabulated critical $\underline{F}$ value was as follows:

$$\underline{F}\ (3,16) = 3.24 < [F_c = 03.71]$$

Table 48

<u>Results Obtained From Tukey HSD Procedure on (E) for The Control and New Cementitious Concrete Composites Containing 5% Aggregate Substitutes</u>

Composite	Control	Glass 5%	Fiberglass 5%	Plastics 5%
$\underline{E}$ (Ksi)	67.31	71.65	81.60	99.40

Table 49

Results Obtained From One-Way ANOVA on (E) for The Control and New Cementitious Concrete Composites Containing 10% Aggregate Substitutes

Source of Variation	df	SS	MS	F_c	p
Treatment	3	2342.74	780.91	03.71	$< .05$
Error	16	3368.73	210.55		

On the other hand, results obtained from the application of Tukey HSD procedure to the same set of data are shown in Table 50 and Appendix I14.

Table 50

Results Obtained From Tukey HSD Procedure on (E) for The Control and New Cementitious Concrete Composites Containing 10% Aggregate Substitutes

Composite	Glass 10%	Control	Plastics 10%	Fiberglass 10%
E (Ksi)	62.54	67.31	70.65	90.93

The obtained results shown above show that no significant differences were identified between the (E) values of the new glass and plastics concrete composites and that value for the control concrete composite. similarly, no significant differences were also identified among the (E) values of the control and new plastics and fiberglass concrete composites. On the other hand, the table shows clearly that the fiberglass concrete composite is better than glass concrete composite in terms of the value of (E).

Fifteen-percent aggregate substitute. The results of the one-way ANOVA for the flexural modulus of elasticity problem case at 15% aggregate substitutes are summarized in

Table 51. The obtained results shown in this Table suggest that at .05 level of significant, there were no significant differences among the average (E) values of the control and new concrete composites containing 15% aggregate substitutes. This is because that the tabulated critical value of F was as follows:

$$F\,(3,16) = 3.24 > [F_c = 02.68]$$

Table 51

Results Obtained From One-Way ANOVA on (E) for The Control and New Cementitious Concrete Composites Containing 15% Aggregate Substitutes

Source of Variation	df	SS	MS	Fc	p
Treatment	03	2513.28	837.76	02.68	> .05
Error	16	5001.66	312.60		

Once more, Tukey HSD procedure was used to enhance the results obtained from using One-way ANOVA and make sure that significant differences can not be identified among the E values for the control and new concrete composites containing 15% aggregate substitutes. Final results shown in Table 52 and Appendix I15 indicate that significant differences were not identified between the (E) values of the control concrete composite and

Table 52

Results Obtained From Tukey HSD Procedure on (E) for The Control and New Cementitious Concrete Composites Containing 15% Aggregate Substitutes

Composite	Plastics 15%	Control	Glass 15%	Fiberglass 15%
E (Ksi)	62.35	67.31	82.19	90.26

all new concrete composites containing 15% aggregate substitutes. This conclusion matches the conclusion obtained from applying One-way ANOVA to the same set of data. This conclusion is also the same as that obtained in the case of 5% aggregate substitute.

Twenty-percent aggregate substitute. The results of the one-way ANOVA for the modulus of elasticity problem case are summarized in Table 53. Again, the results in this Table reveal that at .05 level of significant, there were significant differences among the (E) values of the control concrete composite and those values for the new concrete composites containing 20% aggregate substitutes. This is simply due to the fact that the tabulated critical value of F was as follows:

$$F\ (3,16) = 3.24 < [F_c = 04.79]$$

On the other hand, Tukey HSD procedure was used to identify any significant differences among the control and new concrete composites containing 20% aggregate substitutes. Final results shown in Table 54 and Appendix I16 indicate that the (E) values of the control, glass, and fiberglass concrete composites are not significantly different from each other. Furthermore, no significant differences can be identified between the new concrete composites containing 20% plastics and fiberglass aggregate substitutes and the control concrete composite. The only significant difference that can be identified was between the concrete composites containing 20% plastics and glass aggregate substitutes.

Table 53

Results Obtained From One-Way ANOVA on (E) for The Control and New Cementitious Concrete Composites Containing 20% Aggregate Substitutes

Source of Variation	df	SS	MS	F_c	p
Treatment	03	2605.53	868.51	04.79	< .025
Error	16	2899.29	181.21		

Table 54

Results Obtained From Tukey HSD Procedure on (E) for The Control and New Cementitious Concrete Composites Containing 20% Aggregate Substitutes

Composite	Plastics 20%	Control	Fiberglass 20%	Glass 20%
$\underline{E}$ (Ksi)	61.82	67.31	81.81	90.57

Graphical representation and analysis. The graphical representation for the obtained E values for all the tested cementitious concrete composites in this study is shown in Figure 12. In this Figure, the X-axis represents the percentage of aggregate substitute existed in each concrete composite while the Y-axis represents the average ($\underline{E}$) for these composites. It is to be noticed that the ($\underline{E}$) value for the control concrete composite is represented by a straight line parallel to the X-axis. The Figure also shows the best curve fitting for each category of the new concrete composite containing one of the three waste materials used in this research.

Figure 12 shows that the relationships between the ($\underline{E}$) values and percentages of aggregate substitutes for all the new concrete composites can be represented as polynomial curves of the second degree. Equations 30 through 32 demonstrate the relationships between the flexural modulus of elasticity ($\underline{E}$) and the percentage of aggregate substitutes (p) for the plastics, glass, and fiberglass concrete composites respectively.

$$\underline{E} = 138.50 - 9.40\,(p_P) + 0.28\,(p_P)^2 \quad \text{(Ksi)} \qquad (30)$$

$$\underline{E} = 081.25 - 3.21\,(p_G) + 0.19\,(p_G)^2 \quad \text{(Ksi)} \qquad (31)$$

$$\underline{E} = 063.19 + 4.61\,(p_{FG}) - 0.18\,(p_{FG})^2 \quad \text{(Ksi)} \qquad (32)$$

Again, the values of (p) in the above equations range from 5 to 20 only. Figure 12 shows clearly that the ($\underline{E}$) values for the new fiberglass concrete composites are always higher than that for the control concrete composite along the range of 5 to 20% fiberglass aggregate substitutes. This increase in (E) values ranged from about 21% (at 5% fiberglass aggregate) to 38% (at about 13% fiberglass aggregate). The fiberglass curve shows an increase in the (E) value from 5% to about 13% fiberglass aggregate substitute and then the (E) value goes down again until it reaches the same value of E for 5% fiberglass aggregate at 20% fiberglass aggregate. The curve also shows symmetry about the value of 13% fiberglass aggregate. In other words, the values of (E) at 5 and 20% fiberglass are the same as well as those at 10 and 15% fiberglass aggregate.

In case of the new concrete composites containing plastics aggregate, Figure 12 shows that the reduction rate of the average (E) values of these composites in the range of 5 and 20% plastics aggregate substitute is the highest among all the tested new concrete composites. These (E) values ranged from about 46% above that value for the control concrete composite (at 5% plastics aggregate) to 12% below that value (at about 17% plastics aggregate). The Figure also shows that there is a noticeable difference between the (E) value for the new concrete composite containing 5 % plastics aggregate and that value for the control concrete composite. This observation contradicts the conclusion obtained from the statistical analysis for these data at that percentage of aggregate substitute.

Figure 12 shows also that in case of adding glass waste aggregate substitutes, the behavior of these concrete composites does not resemble that of either plastics or fiberglass aggregate substitutes. The glass curve shows that the (E) value of this concrete composite went down slightly in the region between 5 and about 8% glass aggregate substitute and then gained more stiffness when more glass aggregate substitute was added up to 20%. In addition, the glass curve shows that the (E) values ranged from that similar to the control concrete composite (at about 8% glass aggregate) to 38% above that value (at 20% glass aggregate). This range of E values indicates that the stiffness of all the tested glass concrete composites is at least the same as (or more than) that of the control concrete composite.

Based on the (E) values depicted on Figure 12, the fiberglass cementitious concrete composites are the most consistent composites within the selected range of 5 and 20% aggregate substitutes followed by glass and finally plastics concrete composites. It is very interesting to note that only two new concrete composites (containing 15 and 20% plastics aggregate) have lower stiffness than that of the control concrete composite. The rest of the new concrete composites are as stiff as, or stiffer than, that of control concrete composite.

One of the controversial points that should be addressed here is the conclusions drawn from the statistical and graphical analyses of the collected data. From the statistical analysis standpoint, it has been determined that there is no significant differences among the (E) values for the control and the new concrete composites in the cases of 5 and 15% aggregate substitutes. In the mean time, significant differences have been identified among these composites at 10 and 20% aggregate substitutes. These conclusions contradict those obtained from the graphical analysis of the same data. For example, the difference between 15% fiberglass and plastics concrete composites is about 50%. The same difference is obtained between the 20% glass and plastics concrete composites. However, the statistical analysis indicated that no significant difference was identified in the former case while a significant difference was identified in the latter case. Figure 12 shows clearly that these two pairs of concrete composites have significant differences between each other. Same contradiction can be noticed in the comparison between the maximum and at least the minimum values of (E) in the case of 5 and 10% aggregate substitutes. From the technical standpoint, graphical representation and analysis is more valid than applying statistical analysis methods to the data without enough knowledge about the nature of the problem and drawing superficial conclusions which may not strongly relate to the problem.

Scanning Electron Microscopic Analysis

It is a fact that the properties of any material originate from and are correlated to its internal structure. Consequently, in order to improve the properties of any material, suitable changes in its structure should be considered. However, since the structure of concrete is heterogeneous, changes with time, and is highly complex, the structure-property relationships in concrete are not yet well developed (Mehta, 1986). Therefore, in this part of the study, extra efforts were exerted to conduct visual analysis to generated optical photographs in order to study the general fracture behavior of the control and new concrete composites. Furthermore, the scanning electron microscope (SEM) technique was used to generate micrographs for three objectives. These objectives are as follows:

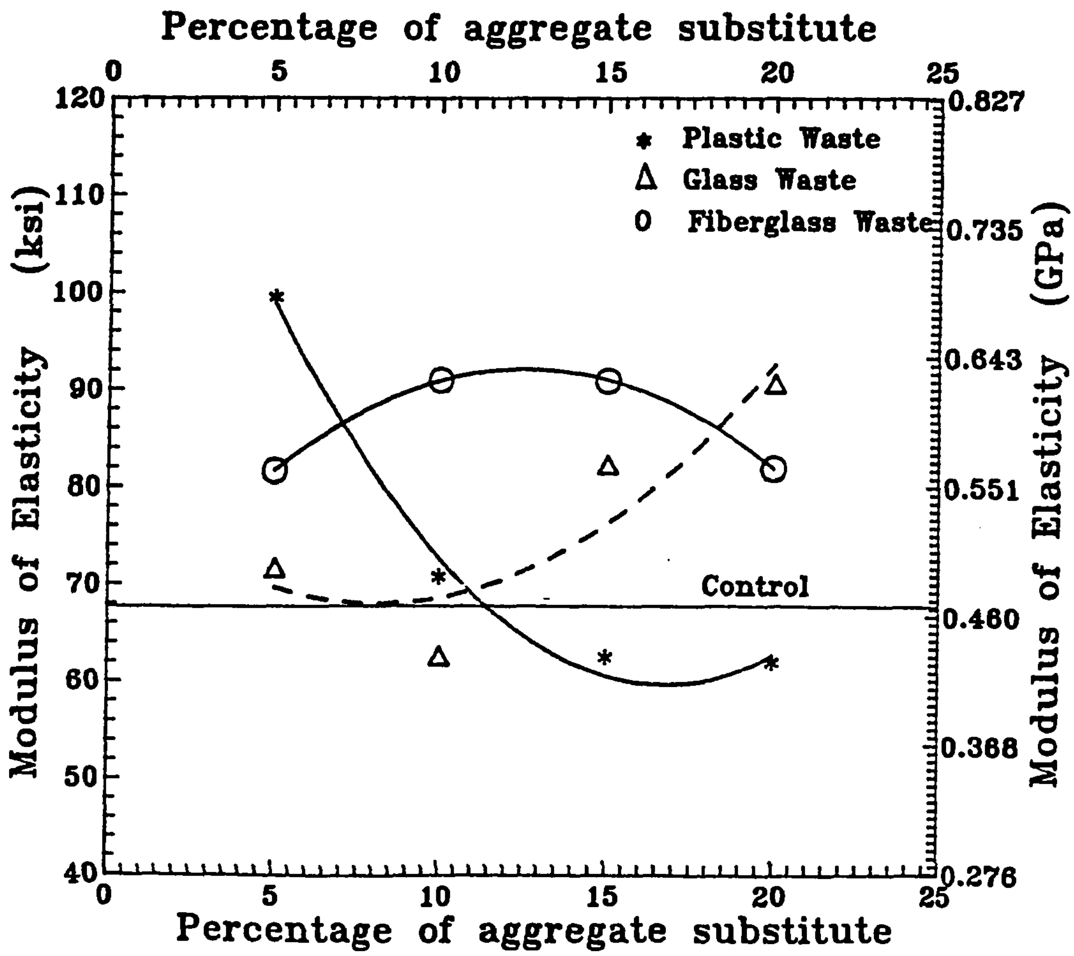


Figure 12. The flexural modulus of elasticity (E) versus the percentage of aggregate substitutes in the new cementitious concrete composites.

1. To visually analyze the morphology of the fine aggregates used in this research before and after mixing them with the other concrete ingredients.

2. To study the microstructure of, and the interfacial bonding between the used aggregates and the cementitious matrix for both the control and the new concrete composites at different aggregate percentages through the visual analysis of the SEM micrographs

3. To visually analyze the crack behavior of each of the tested concrete composites and observe any effects of the types and percentages of aggregates on the features of the cracking systems in these composites.

Of course, all these visual analyses are a trial to establish relationships between the mechanical properties and the microstructures of these composites. This analysis is basically used to answer Research Questions 7 through 12 mentioned in chapter I. The following sections present and discuss the preparations of the samples used to generate both photographs and micrographs and the visual analysis of these graphs.

Preparation of Samples

First of all, after conducting each mechanical testing (i.e. compression, splitting tensile, and flexural tests), all the failed specimens were preserved and carefully handled in order to generate photographs for the general fracture modes for these concrete composites. Samples representing each type of concrete composite at different percentages were selected to generate these photographs. A compact X-7 Minolta camera with different power lenses and appropriate photographing accessories were used to generate all these representative photographs. Black and white and color photographs, which were the end products of the general fracture behavior analysis, were produced by using Kodak 400 ASA films.

In case of the SEM micrographs, representative samples were taken immediately after conducting the compression test for each concrete composite. This is due to the fact that the (f'_c) value of any concrete composite is a principle characteristic in the mix design procedure while both the flexural and splitting tensile strengths can be empirically related to the compressive strength. Also the fracture modes for the flexure and splitting tensile samples appeared to be less complicated than those for the compression ones.

The selected SEM samples were perfectly dried using a three-step technique: (a) air drying for about two weeks; (b) furnace drying at about 70°F for 24 hours: and (c) keeping them in a desiccator to allow them to further dry using a mechanical vacuum pump for a period of two days. This technique was used to assure that the SEM samples are moisture-free. One representative sample from each tested concrete composite was then randomly selected to be coated with gold/palladium for surface conductivity improvement. The sizes of the samples ranged from one to two inches which were appropriate to fit in the sputter coating and the SEM specimen chambers. Anatech sputtering coating machine, available in the electron microscope laboratory at the university of Northern Iowa, was used to coat all the SEM samples. A 50-nm gold/palladium coating layer was sputter-coated on the surface of each sample to improve the image quality and increase the secondary electron yield of the nonconductive concrete samples before examining them in the SEM. The coating time of these specimens ranged from 35 to 50 minutes with a coating rate of 3 nm/min.

After coating the SEM specimens, a silver paste was applied to a few connecting spots between the bottom surface of each sample and the sample holder to allow discharging electrons to the specimen stub and preventing accumulation of these electrons on the surfaces of the specimens which may affect the imaging quality. These specimens were then left for a few minutes to allow the paste to dry before inserting each one of them in the SEM specimen chamber. The accelerating voltages used for image formation of all the tested SEM specimens were 10 and 15 KV. The magnification power ranged from x35 to x800. The desired SEM images for all the tested SEM specimens were recorded by photographing the CRT monitor using attached camera to the Hitachi S-570 SEM, which is available in the electron microscope laboratory at UNI. The recording medium used to obtain the SEM micrographs in this study was black and white Polaroid 4" x 5" (positive/negative) film. The photo scan speed for each CRT image was 100 seconds with a 25-second developing time to obtain each positive/negative micrograph.

Visual Analysis of The Cementitious Concrete Composites

The following sections describe the morphology of all the fine aggregates used in this research study. The features of the sand, plastics, glass, and fiberglass aggregates before mixing them with the other constituents of the control and new concrete composites will be presented using the SEM micrographs. The microstructures of all the control and new concrete composites at different percentages of aggregate substitutes will be also demonstrated. The interfacial bonding between the used aggregates and cementitious matrix in the control and new concrete composites at different aggregate percentages will also be discussed through the visual analysis of these SEM micrographs. Finally, visual analysis of the crack behavior of each one of the tested concrete composites and observation of any effects of the types and percentages of aggregates on the features of the cracking systems in these composites will be presented.

Morphology of The Fine Aggregates

Figure 13 shows the microstructure of the fine aggregates (sand) used in this research study at a magnification of X50. The shapes and surface textures of these aggregates were a combination of the following: (a) rounded and smooth particles; (b) equidimensional crushed rocks; and (c) rough and angular particles. It is to be also noticed that these fine aggregates were clean, hard, durable, and uncoated particles. They were free from organic matter, vegetable loam, alkali, or other deleterious substances that could affect the hydration and bonding processes of the cement paste. This combination of fine and coarse sands worked together to produce concrete composites with satisfactory workability and strength requirements. This is simply due to the fact that the coarse sand particles can secure the desired strength by keeping the water and cement requirement unchangeable while the fine ones play an effective role in producing workable concrete mixtures (Kosmatka & Panarese, 1988). The existing combination of the fine aggregates used in this study had 2.7 fineness modulus (FM). The majority of the sand sizes were between sieve #100 (150 μm) and sieve #8 (2.36 mm).

Figure 14 shows the microstructure of the glass aggregate substitute (which is a combination of both clear window glass and fluorescent bulbs) at a magnification of X40.

These crushed glass aggregates had predominant angular shapes with sharp edges. The sizes of these aggregates ranged mostly from sieve #100 (150 μm) to sieve #8 (2.36 mm). The surface textures of these aggregates were a combination of smooth and rough surfaces. The roughness appeared on some of these surfaces was partially attributed to the crushing machine which left some sirration marks on these surfaces. It is to be mentioned that these glass aggregates were hard and durable but mixed with a small amount of contaminants and large size particles as shown in Figure 14. The value of FM of these glass aggregate waste was 2.1 which means that the glass aggregates were finer than the sand aggregates.

The microstructure of the plastics aggregate waste can be seen in Figure 15 at a magnification of X40. This aggregate waste was a combination of both the PET (soda bottles without metal caps and paper labels) and HDPE (milk jugs). The micrograph also shows a small amount of contamination mixed with these two plastic materials. It is to be noticed that these plastic aggregates had a wide range of aggregate sizes and shapes. The sizes of these aggregates ranged mostly from sieve #100 (150 μm) to sieve #16 (1.18 mm). Particles with flat, rounded, elongated, and angular shapes can easily be found in this micrograph. Smooth and rough surfaces can also be seen. The value of FM for plastics waste material used in this study was higher than that of sand (3.4 to 2.7 respectively). This makes these plastic aggregates to be the coarsest fine aggregate used in this research study. Again, these fine aggregates were clean and uncoated particles like those of sands.

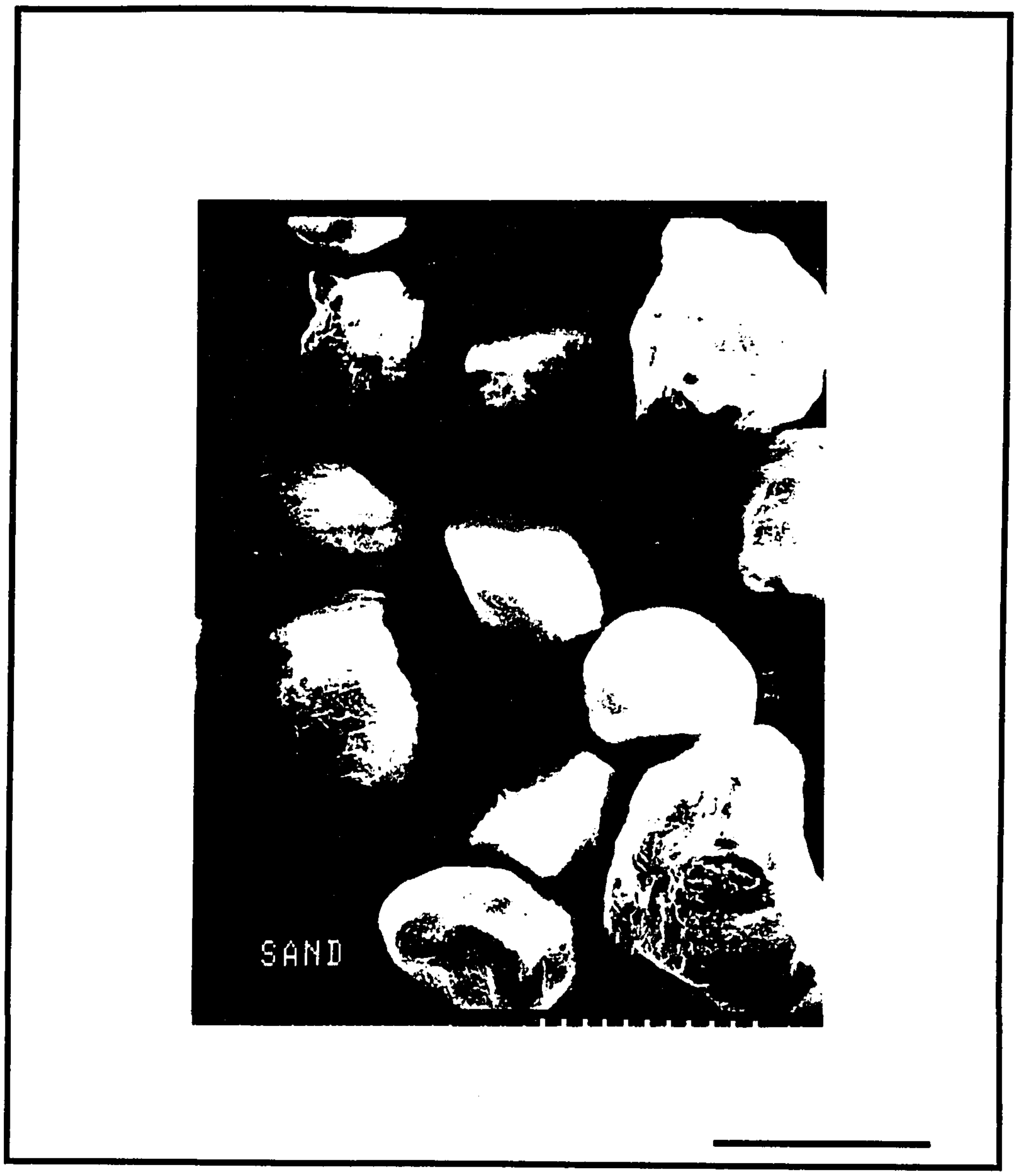
Figure 16 shows the microstructure of the fiberglass aggregates at a magnification of X120. It is to be mentioned that these waste aggregates were a combination of unsaturated polyester base resin, styrene, continuous filament fiberglass, catalyst (Methyl Ethyl Ketone Peroxide), triethyl phosphate (TEP), gelcoats (styrene), and less than 0.5% contaminants (solem alumina trihydrate and calcium carbonate). These base resin, styrene, continuous filament fiberglass, and gelcoats can be clearly seen in Figure 16. The diameter of the continuous and smooth filament fiberglass was about 17 μm (about 0.0007 inch) with lengths ranging from about 50 μm (about 0.002 inch) to as long as one mm (about 0.04 inch). The sizes of these fiberglass aggregates ranged mostly from sieve #100 (150 μm) to sieve #4 (4.75 mm). The value of the FM of the fiberglass aggregate waste was

1.6. This value makes the used fiberglass aggregate substitute considered to be the finest aggregate substitute used in this research study.

Visual Analysis of The Cementitious Control Concrete Composite

Figure 17 shows an SEM micrograph at a magnification of X60 for a fractured control concrete composite. This micrograph shows that a coarse aggregates (GR) and voids which dispersed in a matrix of the dehydrated cement paste (hcp). It can be noticed that the GR and hcp of the concrete structure are not homogeneous and are heterogeneously distributed with respect to each other. The micrograph also shows that the cracking systems (C) have occurred in two phases: the hcp phase and the interfacial region (transition zone) between the GR and the hcp. Another micrograph was taken at a magnification of X250 for the same concrete composite (Figure 18) shows that the cracking systems extended in the transition zone (tz) and underneath the GR which were pulled out (upon debonding) from the composite. It is to be noticed also that some dehydration products in the form of calcium hydroxide (CH) crystals existed and scattered in the empty grooves (resulted from pulling out the gravels), voids, and the surface of hcp.

Figure 19a shows the general fracture behavior of the control concrete composite under compression load. The type of fracture is of cone and split shape which conforms to the ASTM standard (1991b). The Figure also shows the resulted main cracks along the loading axis separating this specimen into a few chunk pieces. Multi microcracks were also initiated and propagated in the hcp and tz phases causing failure in the control composite. Figure 19b shows the general fracture behavior of the same concrete composite under center-point loading. Almost all the tested flexural specimens experienced In-Plane shear fracture on the upper surface which is in contact with the applied load. However, the side surfaces were fractured with a shear angle of about 20^{o} to the axial load. Figure 19c shows the general fracture behavior of the control composite which resulted from the splitting tensile test. The main cracks due to brittle failure along the diametral loading axis are created which caused the specimen to split into two halves. Some microcracks occasionally may branch from the main cracks due to the possibility of the existence of dense areas of



X50 10 KV 0.60 mm

Figure 13. SEM micrograph of the sand aggregates.

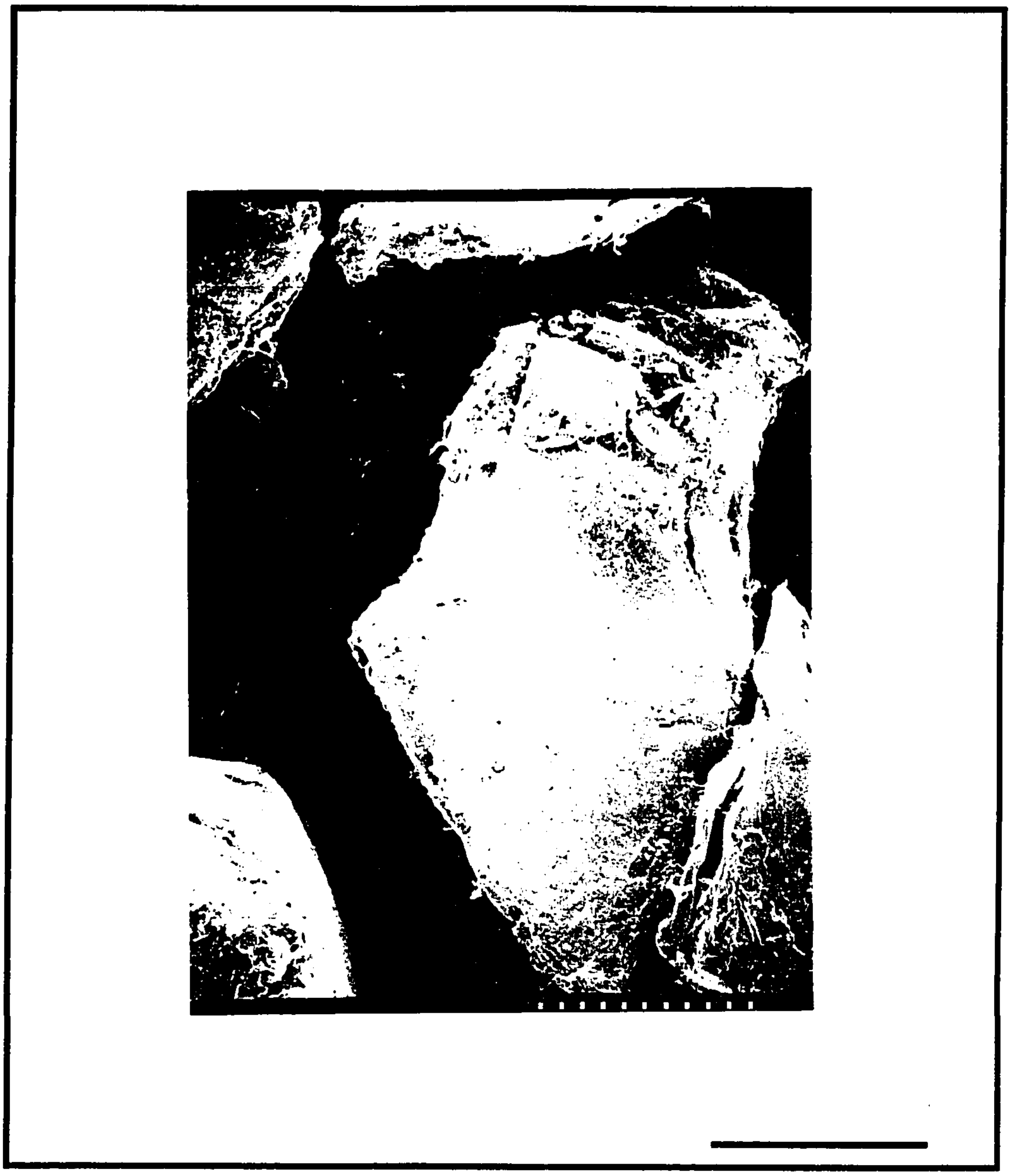
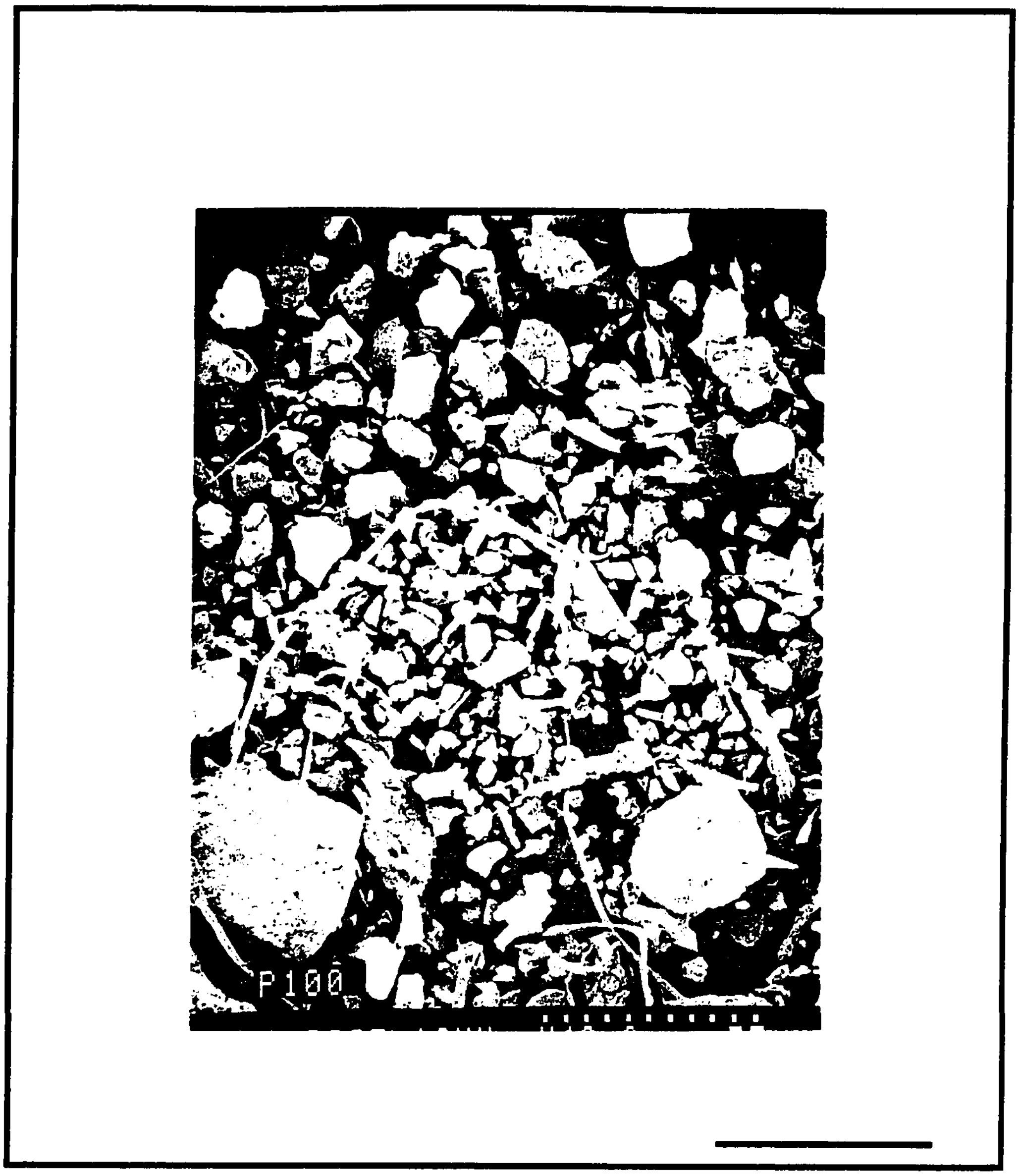
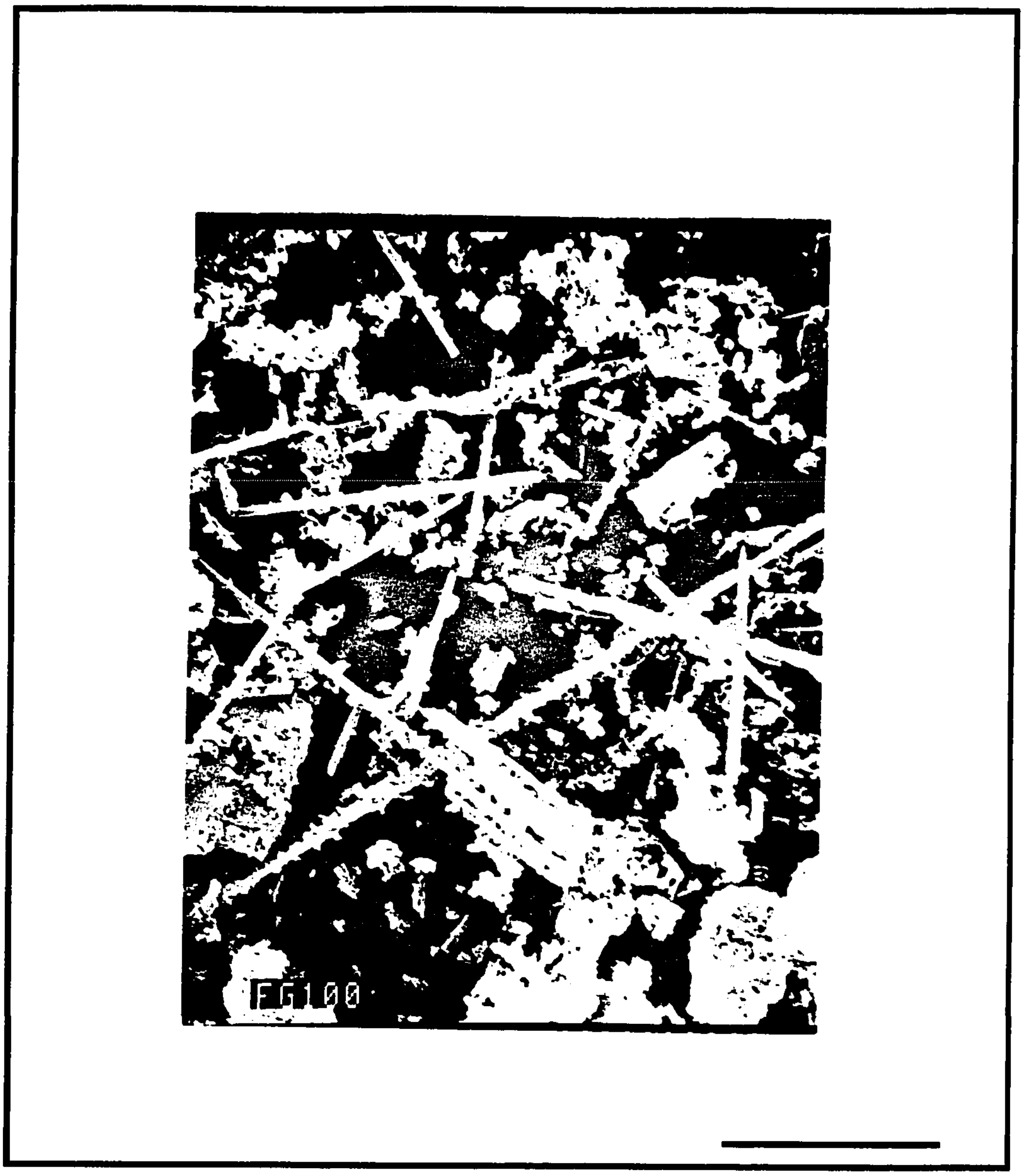


Figure 14. SEM micrograph of the glass aggregates.



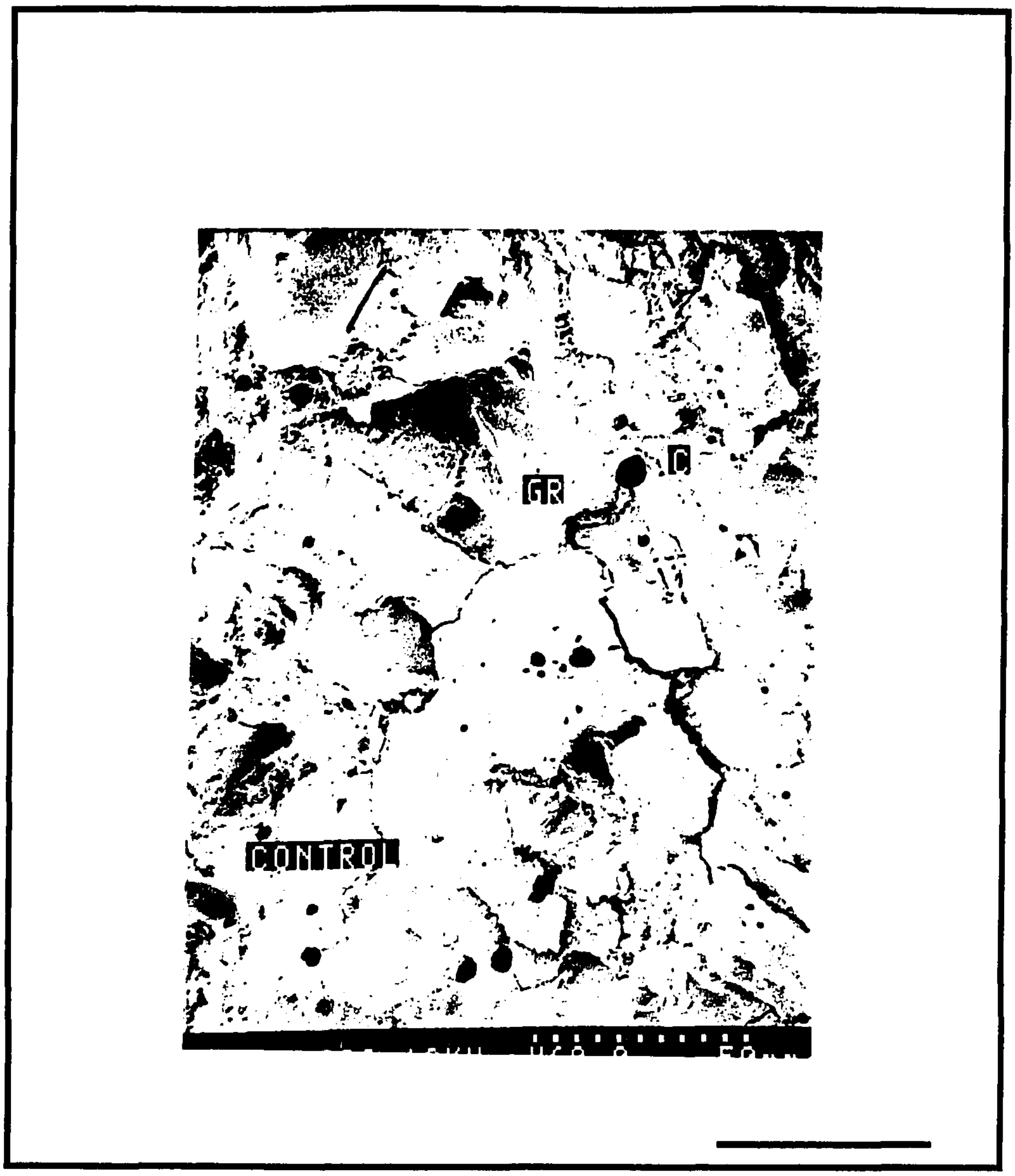
X40 10 KV 0.75 mm

Figure 15. SEM micrograph of the plastics aggregates.



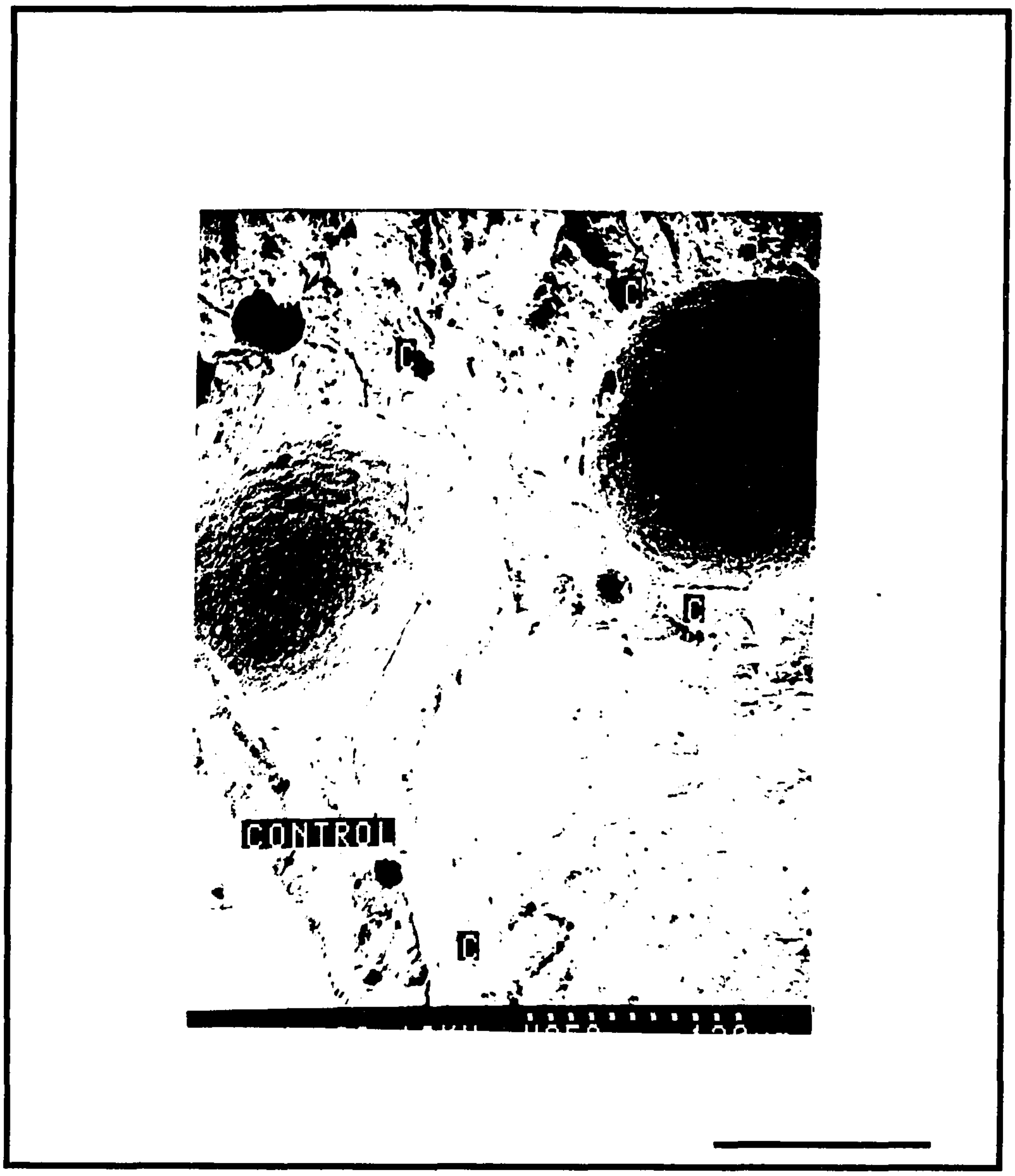
X120 10 KV 250 μm

Figure 16. SEM micrograph of the fiberglass aggregates.



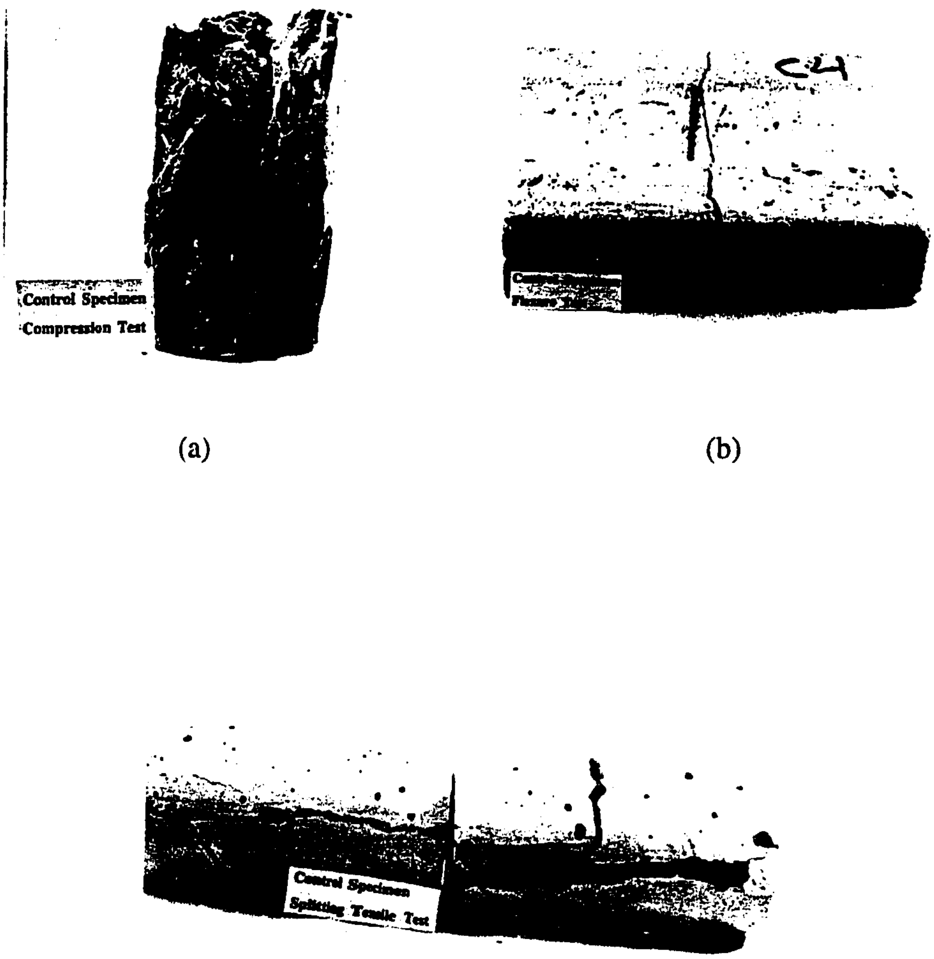
X60 10 KV 0.50 mm

Figure 17. SEM micrograph of a fractured control concrete composite.



X250 10 KV 120 μm

Figure 18. SEM micrograph for the cracking systems in a control concrete composite.



(a) (b)

(c)

Figure 19. General fracture behavior of control concrete composite.

(a) Specimen under compression test.

(b) Specimen under flexural test.

(c) Specimen under splitting tensile test.

voids near the main cracks as can be seen from Figure 19c. These microcracks may produce other main cracks across the diameter of the tested specimen.

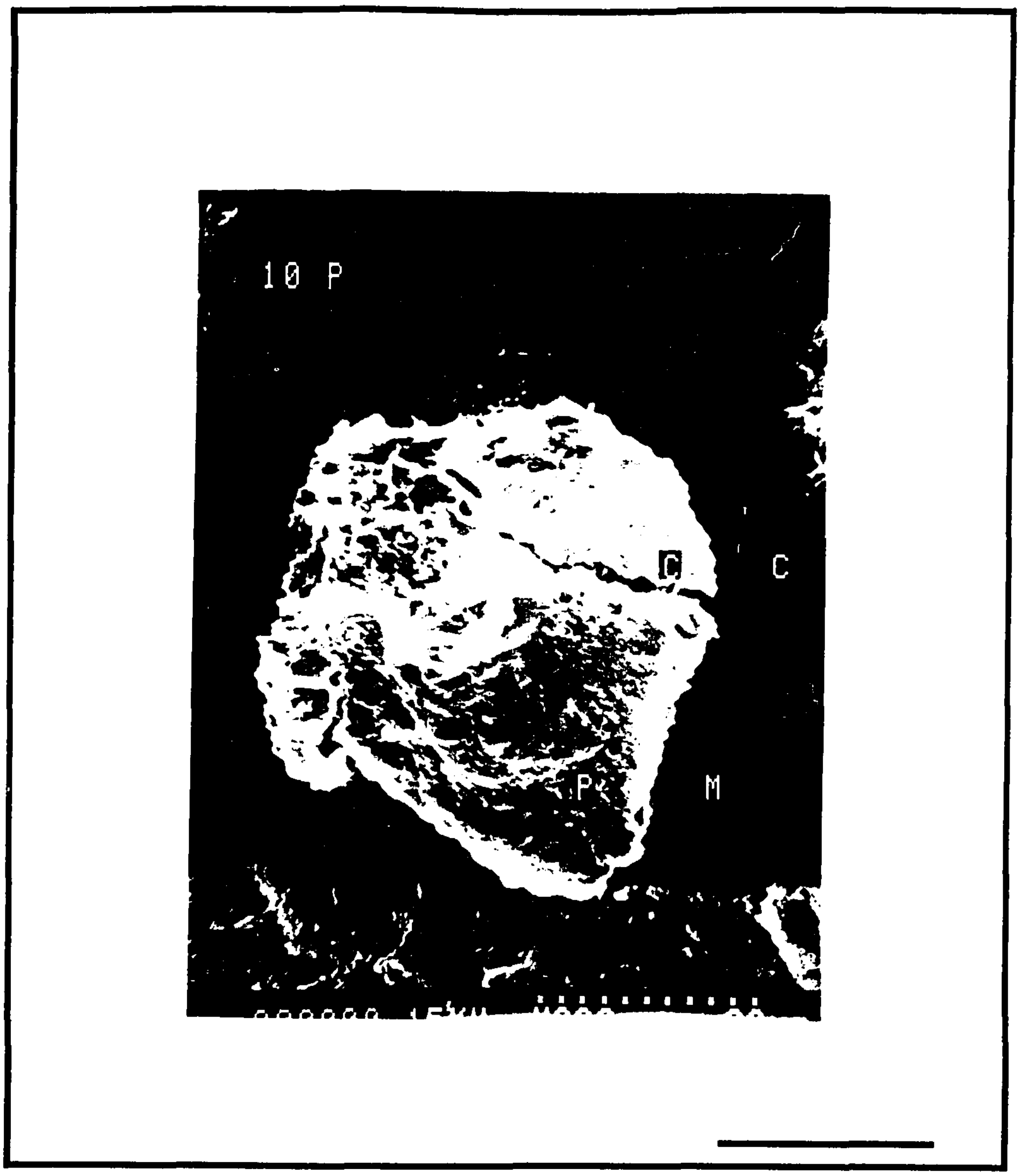
Visual Analysis of The New Plastics Concrete Composites

In the case of the control concrete composite, the sand aggregate strength was not a crucial factor in the concrete strength because these aggregates were extremely stronger than the strengths of the hcp and the tz in concrete. This is actually true since the failure of the concrete is determined by the other two phases (hcp and tz) and not by the aggregate phase. However, the situation is different in case of using plastics waste material as a partial aggregate substitute for sand aggregate in concrete composite. It is well known that plastics aggregates are lighter in weight and weaker in strength than the sand aggregates. Having this fact in mind, failure in concrete composites containing plastics substitute can be expected in all the three phases: hcp, tz, and plastics aggregate phases. This expectation was proven true by analyzing the concrete composite microstructure using SEM technique. Figure 20 shows the failure in the plastics aggregate phase in a cementitious concrete composite containing 10% plastics aggregate substitute at a magnification of X800. The micrograph shows that the cracking system (C) went through the hcp (or the concrete matrix M) and propagated through the plastics aggregate causing this aggregate to shear.

It is to be noticed in Figure 20 that there is no appropriate bonding between the plastic aggregate and the cement paste. This simply means that the plastic aggregates substitute was only used as a filler in the concrete composite. This observation was repeated in all the SEM micrographs produced for all the concrete composites containing different percentages of plastics aggregates. An example of the failure which occurred in the other two phases (hcp and tz) in the concrete composites can be seen in the SEM micrograph (Figure 21) for the 5% plastics concrete composite at a magnification of X60. It is to be noticed in this figure that the amounts of what appears to be the CH crystals and plastic particles (existed and scattered in the empty grooves, voids, and the surfaces of hcp and tz) are more than that amount of CH crystals exited in the control concrete composite. These amounts were increased by the increase of the percentage of plastics aggregate substitute used in concrete composites.

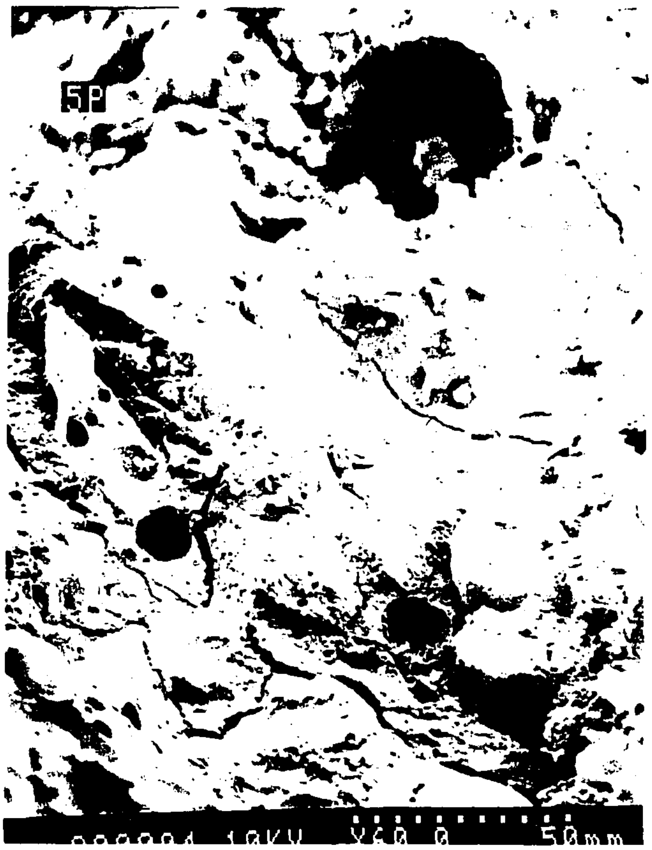
Based on Table 6 (which was discussed earlier in this chapter) and from the concrete mix design point of view, both the gravel and water contents were supposed to be reduced while the sand and plastics waste contents were supposed to be increased in all the new plastics concrete composites. In other words, these new concrete composites had more water and gravel while they were short of sand and plastics aggregates. The continuous increase of the water content in these composites and consequently the water/ cement ratio directly affected the porosity in the hcp and tz phases and their strengths. Mehta (1986) mentioned that at later stages, the typical behavior of concrete is to have weaker hcp phase than the tz phase. This statement holds true and is supported by visual observation of SEM micrographs shown in Figures 22 and 23. These two Figures show the microstructure of new concrete composites containing 15 and 20% plastics aggregate substitute at a magnification of X280 and X270 respectively. It is noticed in these Figures that the amounts of what appears to be the CH crystals and plastic particles were increased in these concrete composites. Yet, there is no bonding in the transition zone between the plastic aggregates and concrete matrix. It appears that the weakness in the hcp and the plastics aggregate phases might have been attributed to the reduction of the compressive strength of the new plastics concrete composites. An exception of this conclusion is the sudden increase in the compressive strength of the concrete composite containing 20% plastics aggregate substitute. It appears that when the plastic aggregates were increased to that volume percentage, the cracking energy needed to propagate the initial microcracks and cause fracture of the concrete composite was also increased to overcome the existence of this amount of aggregates. This amount of plastic aggregates might have increased the resistance of this composite to cracking.

In general, the plastic aggregates worked as crack arrestors and energy absorbers in the new plastics concrete composites tested in this research study as evidenced in Figures 22 and 23. The existence of these plastic aggregates was also one of the main reasons to hold the shape of the concrete cylinders tested under uniaxial compression load even after complete failure of these cylinders.



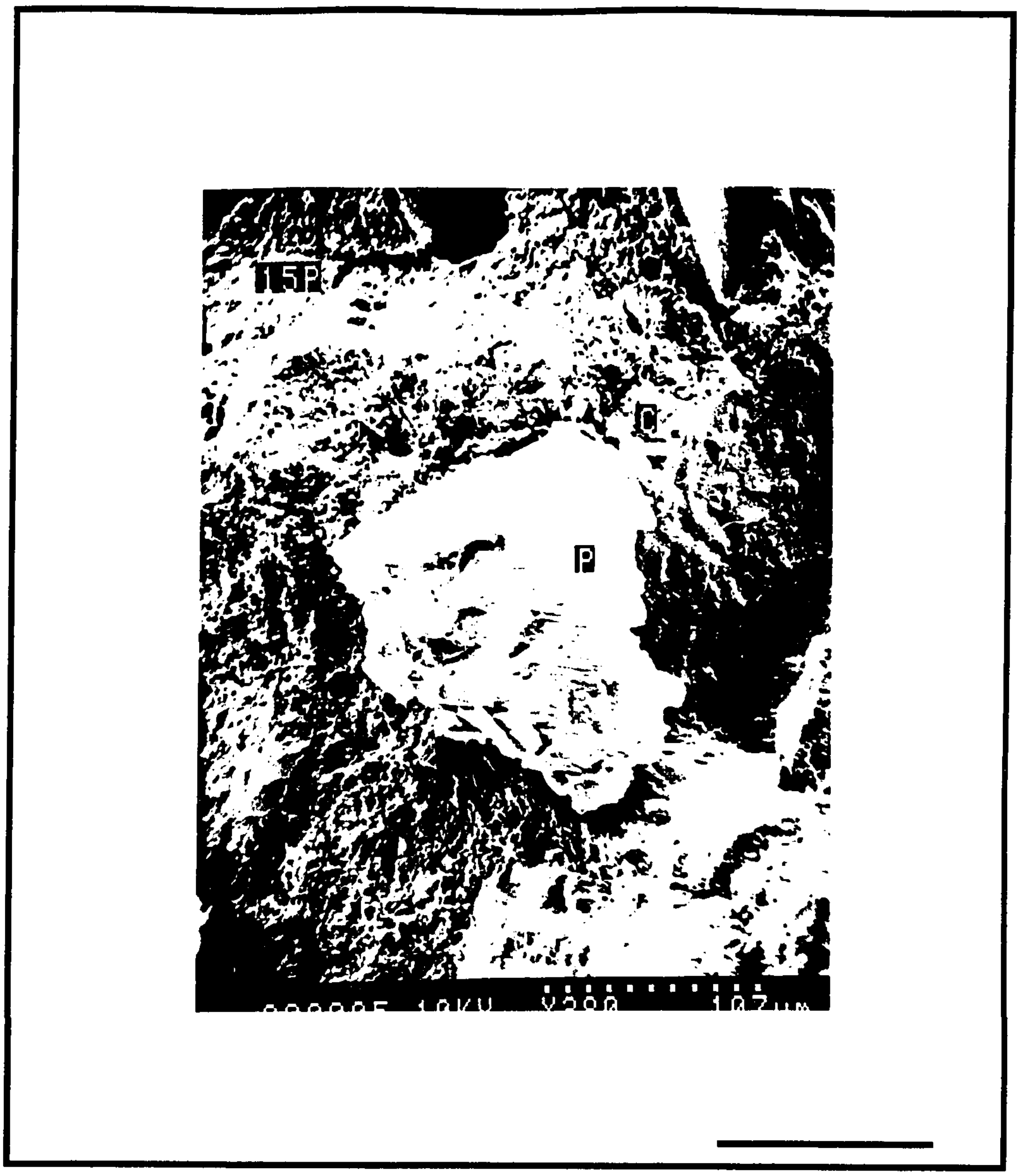
X800 15 KV 38 μm

Figure 20. SEM micrograph for the failure of the plastics aggregate phase in cementitious concrete composite containing 10% plastics aggregate substitute.



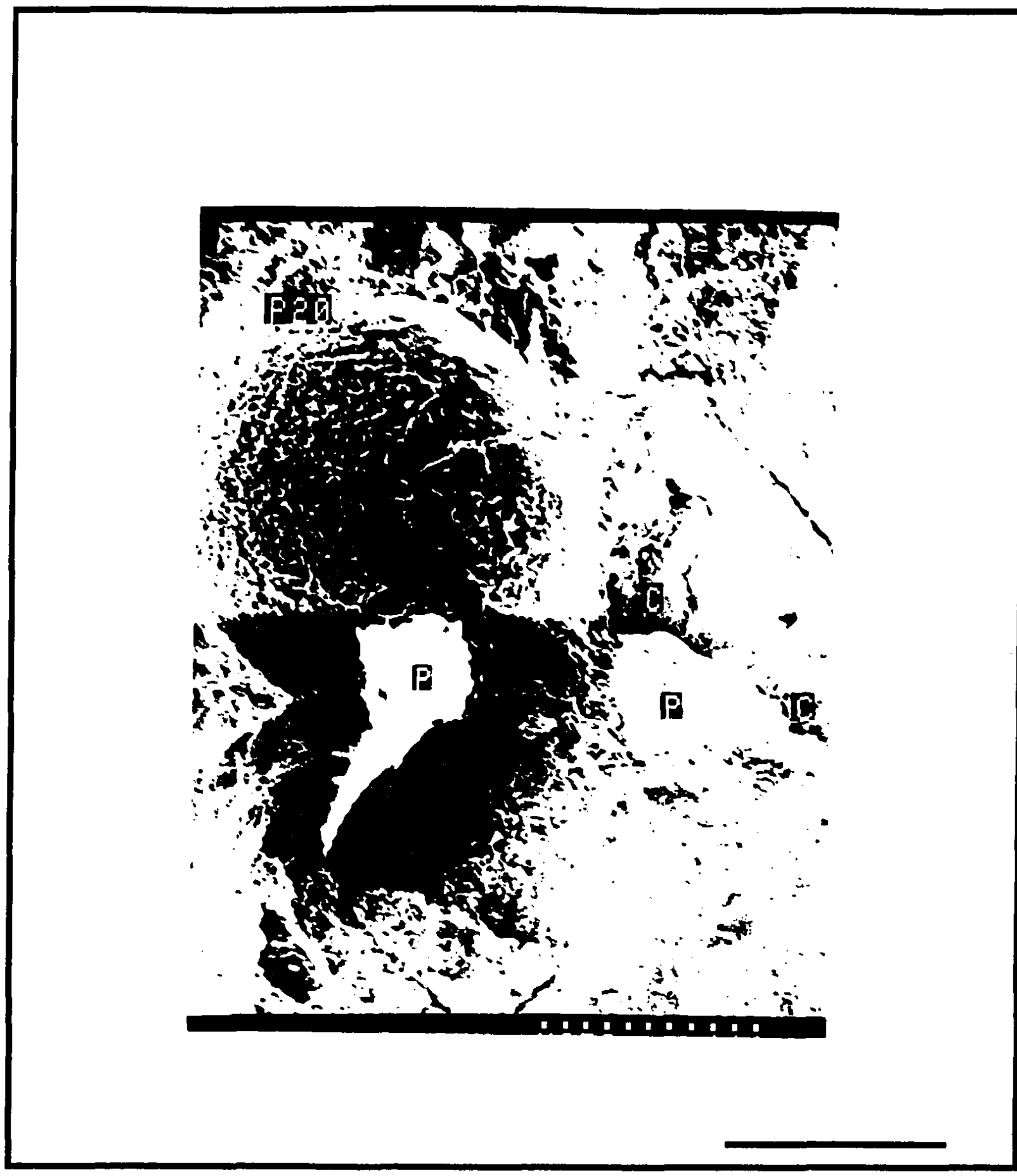
X60 10 KV 0.50 mm

Figure 21. SEM micrograph of the failure of the tz and hcp phases in a cementitious concrete composite containing 5% plastics aggregate substitute.



X280 10 KV 107 μm

Figure 22. SEM micrograph of a fractured concrete composite containing 15% plastics aggregate substitute.



X270 10 KV 111 μm

Figure 23. SEM micrograph of a fractured concrete composite containing 20% plastics aggregate substitute.

This phenomenon can be easily seen in Figure 24(a-d) which shows the general fracture behavior of the concrete composites at different percentages of plastics aggregate substitute. As noticed in this figure, the appearance of the fractured 20% plastics concrete cylinders (Figure 24d) is almost the same as the original ones before testing. The completeness of the shape of these cylinders were followed by those containing 15, 10, and 5% plastics aggregate (Figures 24c, 24b, and 24a respectively). It is to be also mentioned that slight differences in the fracture behaviors of both the control and 5% plastics concrete cylinders can be observed. It is a point of interest to reexamine the fracture behavior of the 15, and 20% plastics concrete cylinders. These cylinders experienced complete failure, yet they held their shapes after failure. These general fracture behaviors of different plastics concrete composites shown in Figure 24 call for utilizing these new cementitious concrete composites in different possible applications (such as buildings; highways; unstable environmental areas exposed to tornadoes, earthquacks, and others) where human lives are involved and holding the shape of the structure for a period of time for evacuation, for example, is of a great importance.

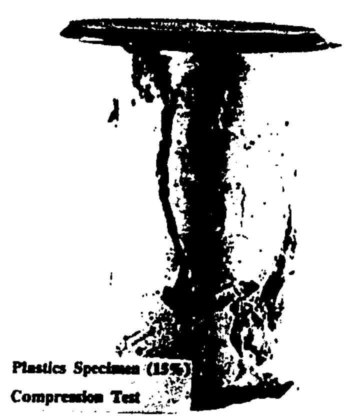
The behavior of plastics concrete composite under splitting tensile loads is characterized by some important differences than their behavior under uniaxial compression load. In case of the splitting tensile testing, the direction of the propagation of every new crack was transverse to the direction of the splitting tensile stress. This growth of cracks reduced the available loading-carrying area causing an increase in the stresses at critical crack tips. The failure of the tensile splitting specimens needed only a few bridging cracks. This was due to the decrease of the frequency of crack arrests rather than the numerous cracks found in the case of concrete specimens tested under uniaxial compressive stresses. This means that splitting tensile specimens experienced rapid crack propagation than those tested under compressive stress. This observation was shown repeatedly with all the new plastics concrete composites (as well as control concrete composite) under splitting tensile stress as can be seen in Figure 25. This Figure shows the general fracture behavior for all the tested splitting tensile specimens containing different percentages of plastics aggregate substitute which are almost identical. This observation coincides with the results obtained from the statistical analysis of the collected data (i.e. it has been proven statistically that the average (T) values of the plastics concrete composites are almost the same in the range of 5 to 20% plastics aggregate substitute). Furthermore, from the statistical analysis, the conclusion that all the (T) values obtained for the new plastics composites were way below that of the control concrete composite may also be supported by the visual analysis of the obtained photographs for the general fracture behaviors of these composites. Since the plastics specimens had weaker phases and more initial microcracks than those phases and initial microcracks in the control composite, the crack propagation in the plastics concrete composites was faster than that in the control composite. This resulted in more than one main crack (which is shown in Figure 19c for the control specimen) in case of plastics concrete specimens as can be seen in Figure 25. It is also to be mentioned that unlike the control specimen, the majority of the plastics concrete specimens tested under splitting tensile stress experienced stress relaxation at the maximum applied stress before failure.

Figure 26 shows the general fracture behavior of the four new plastics concrete composites under center-point loading. Similar to the behavior of the control specimen, almost all the tested flexural specimens experienced In-Plane shear fracture on the upper surface which was in contact with the applied load. On the other hand, the side surfaces were fractured with a shear angle that ranged from 20° to 30° with respect to the axial load.

Visual Analysis of The New Glass Concrete Composites

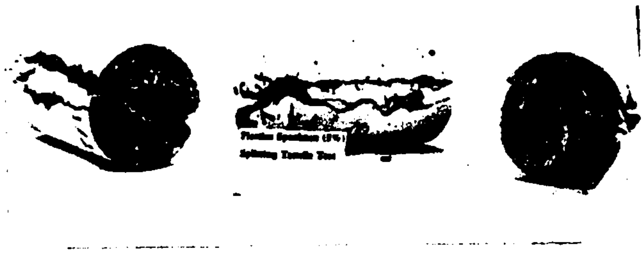
Table 6 shows that the overall FM in case of glass concrete composites decreased with the increase of the glass aggregate substitute percentage. From the concrete mix design standpoint, the reduction in the overall FM means that these concrete composites had less water and gravel while they had surplus of sand and glass. The continuous reduction of the water content and consequently the water/cement ratio directly affected the porosity in the tz and hcp phases and their strengths in these composites. Kosmatka and Panarese (1988) stated that the range of voids contents for coarse aggregates (from about 30% to 45%) is less than that for fine aggregates (from about 40% to 50%). They also mentioned that the angularity of the aggregate shape increases void content. It is to be

(a) 5% plastics aggregate substitute (b) 10% plastics aggregate substitute



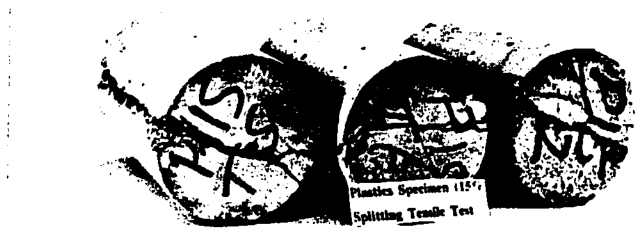
(c) 15% plastics aggregate substitute (d) 20% plastics aggregate substitute

Figure 24. General fracture behavior of new plastics concrete composites at different percentages of aggregate substitute under uniaxial compressive load.

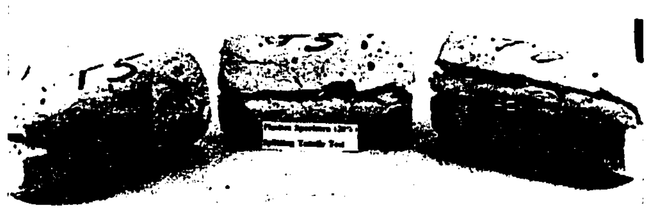


(a) 5% plastics aggregate substitute

(b) 10% plastics aggregate substitute

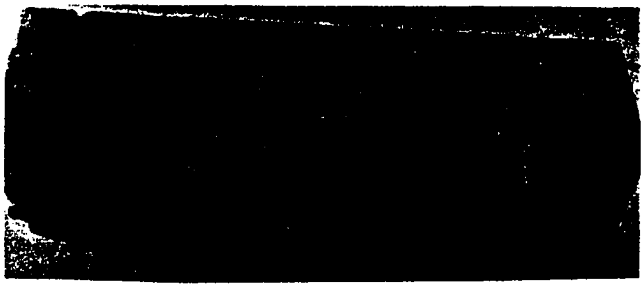


(c) 15% plastics aggregate substitute



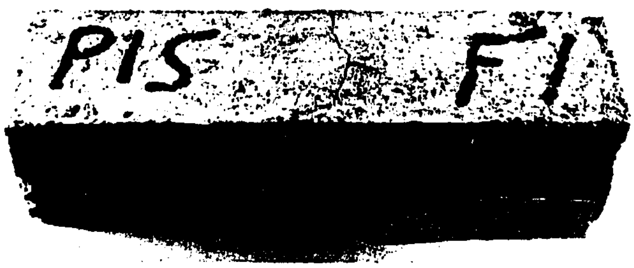
(d) 20% plastics aggregate substitute

Figure 25. General fracture behavior of new plastics concrete composites at different percentages of aggregate substitute under splitting tensile stress.

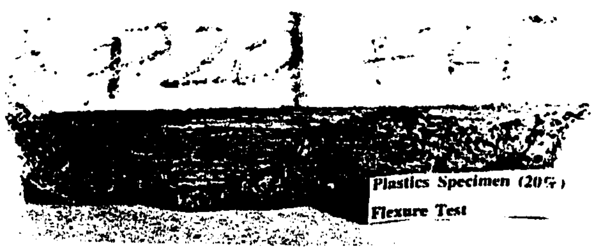


(a) 5% plastics aggregate substitute

(b) 10% plastics aggregate substitute



(c) 15% plastics aggregate substitute



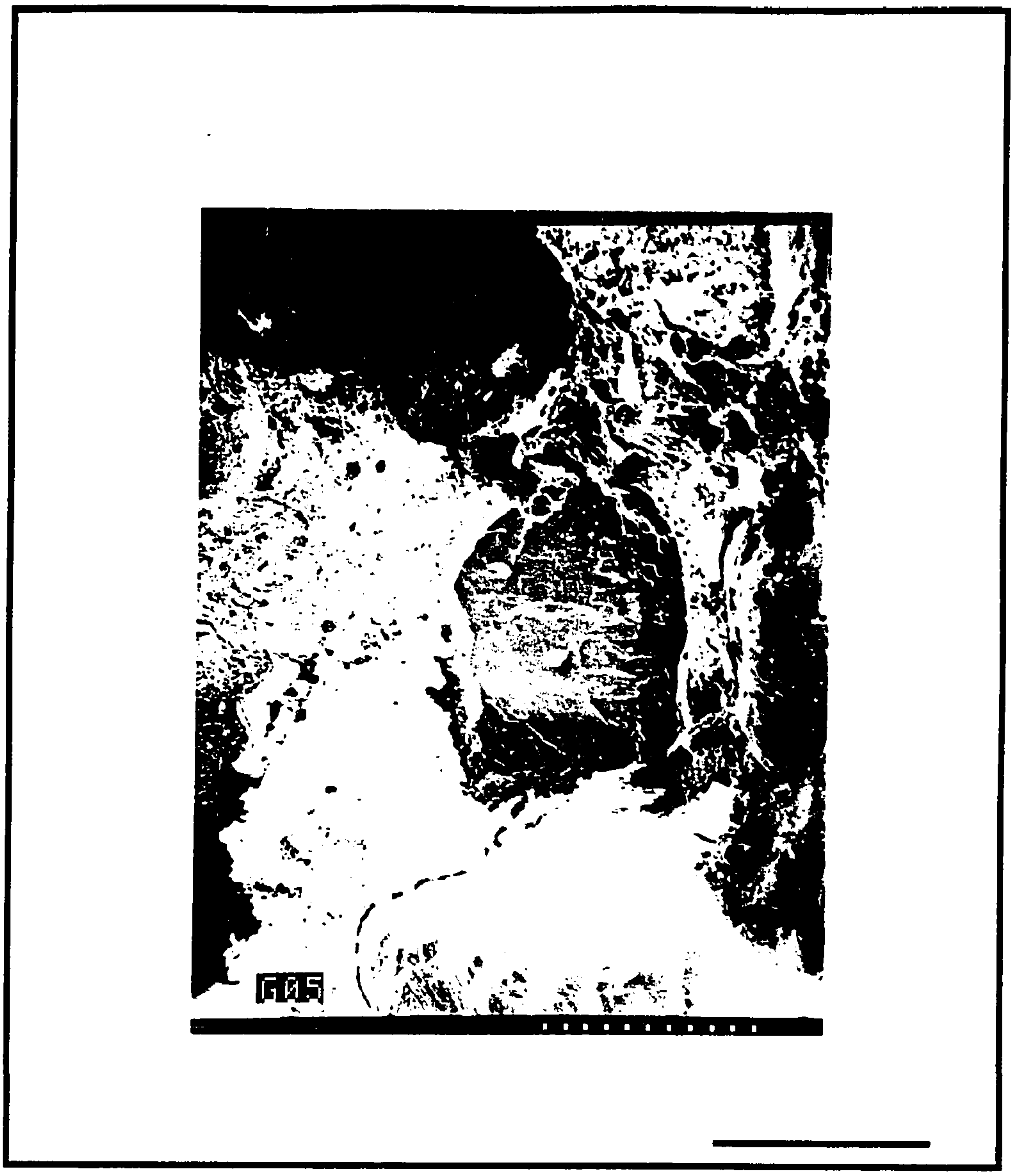
(d) 20% plastics aggregate substitute

Figure 26. General fracture behavior of new plastics concrete composites at different percentages of aggregate substitute under center-point loading (flexure test).

remembered that in this research study, the glass waste aggregates used were finer than the sand aggregates and had predominant angular shapes with sharp edges. This might have led to the fact that the new glass concrete composites appeared to have more voids in the tz and hcp phases that can affect the strengths of these phases and composites.

Figures 27 through 30 show the microstructure of the new concrete composites containing 5, 10, 15 and 20% glass aggregate substitute at a magnification of X130, X200, X110, and X80 respectively. A general observation that can be drawn from these Figures is that unlike the plastics concrete composites microstructure, there appears to be an interfacial bonding between the used glass aggregates and the cement paste in the glass concrete composites. It can be also seen that these glass aggregates worked as crack arrestors and no crack propagation occurred through them. This is due to the fact that these glass aggregates had higher strength compared to those of the tz and the hcp (as well as plastics aggregates) phases. It is to also be mentioned that the amounts of porosity, CH crystals and crack growth and branching were directly related to the amount of glass aggregates that existed in the concrete composites. However, in the cases of 5 and 10% glass concrete composites, the glass aggregates were far apart from each other due to their low amounts while these aggregates were more closer and filled many voids in cases of 15 and 20% glass concrete composites. This may account for the reduction of the f'_c in the first two cases (5 and 10%) and the sudden increase in the second two (15 and 20%).

It is noticed in Figure 28 that the microcracks which were initiated in the tz phase (specifically from the tips of the aggregates which contact them with the cement paste) had propagated in the hcp phase in a branching fashion. It also appears in this Figure that propagation of cracks was stopped by the glass aggregates which arrested other microcracks coming from surrounding directions. This observation is also enhanced by Figure 29 which shows the pull-out phenomenon as well. It seems from Figure 29 that one glass aggregate (gray dark area) was pulled out from its place where a propagated crack was coming from the right bottom part in this figure toward this aggregate. After pulling this glass aggregate out, the propagated crack was arrested by another glass aggregate, shiny gray area with sirration marks across it. In comparison between the microstructures



X130 10 KV 231 μm

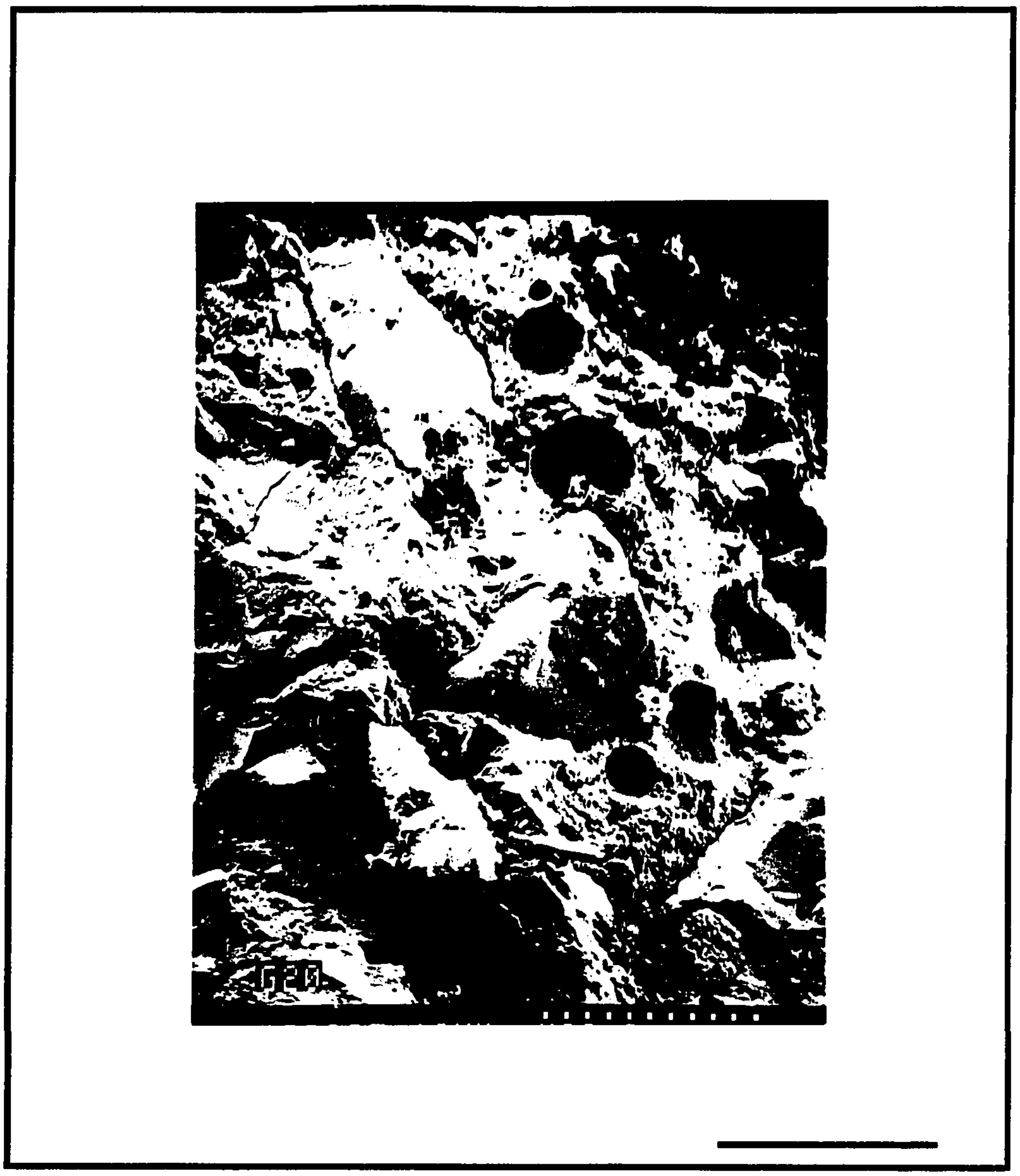
Figure 27. SEM micrograph of a fractured concrete composite containing 5% glass aggregate substitute.

X200 10 KV 150 μm

Figure 28. SEM micrograph of a fractured concrete composite containing 10% glass aggregate substitute.

X110 10 KV 0.27 mm

Figure 29. SEM micrograph of a fractured concrete composite containing 15% glass aggregate substitute.



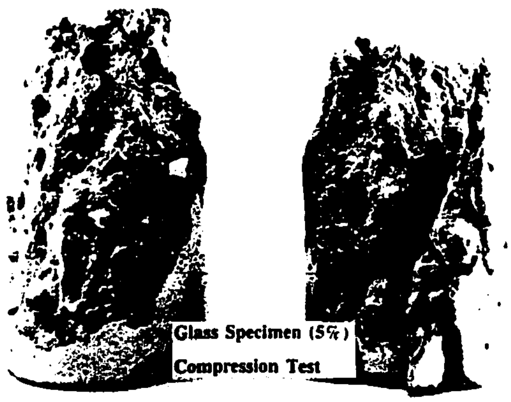
X80 10 KV 0.38 mm

Figure 30. SEM micrograph of a fractured concrete composite containing 20% glass aggregate substitute.

of the plastics and glass concrete composites, it can be seen that the amounts of the CH crystals in the concrete composites at different glass percentages are less than those amounts of CH crystals exited in the counterpart concrete composites at different plastics percentages. It is to also be mentioned that there are some similarities between the microstructures of the control and 20% glass concrete composites (e.g. cracking systems, interfacial bonding, voids contents, and others). This may account for why the average fc' values of these two composites were not significantly different from each other.

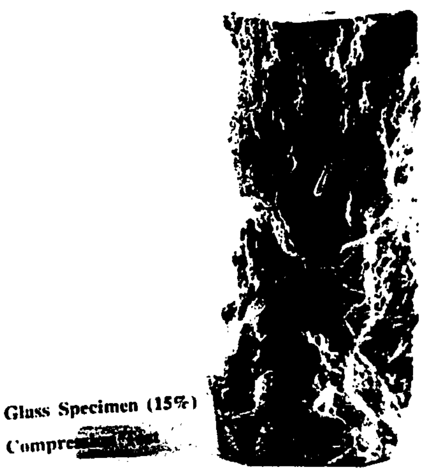
It appears from the present study that the glass aggregates acted as crack arrestors and bonded in a similar fashion as the gravel and sand aggregates in the new glass concrete composites. Figure 31 shows the general fracture behavior of the new glass-containing concrete composites. The majority of the tested cylinders experienced shear, or cone and shear type of fracture which conforms with the fracture types sketched in the ASTM standard (1991b). A combination of columnar and shear fracture modes was also experienced by one of the tested cylinders. It can be noticed that the appearance of these concrete cylinders is different than that of the control composite.

Figures 31a and 31c show concrete cylinders containing 5% and 15% glass aggregate failed by shear mode. On the other hand, Figures 31b and 31d show 10% and 20% glass concrete cylinders failed by combinations of shear and columnar and shear & cone modes respectively. It is to also be mentioned that the slight differences in the fracture behaviors of both the control and the 20% glass concrete cylinders can be observed. It is a point of interest to compare the fracture behavior of the glass to that of the plastics concrete cylinders. While the glass concrete cylinders were shattered into small pieces upon failure, most of the plastics concrete cylinders completely failed and yet held their shapes after failure. This can be attributed to the role played by each of these two waste materials in their concrete composites. In other words, the brittleness of the glass material helped its composites to be more stiffer than those composites containing ductile plastics aggregate specially at higher aggregate percentages. This interpretation, in general, coincides with the trend of the flexural modulus of elasticity obtained from the statistical analysis of the collected data as discussed earlier.



(a) 5% glass aggregate substitute

(b) 10% glass aggregate substitute

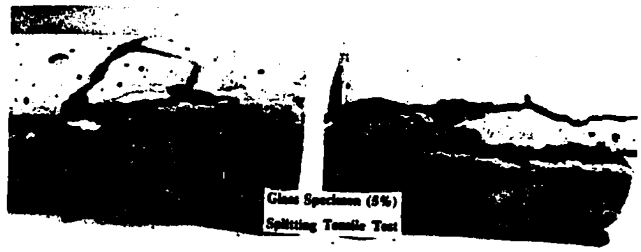


(c) 15% glass aggregate substitute

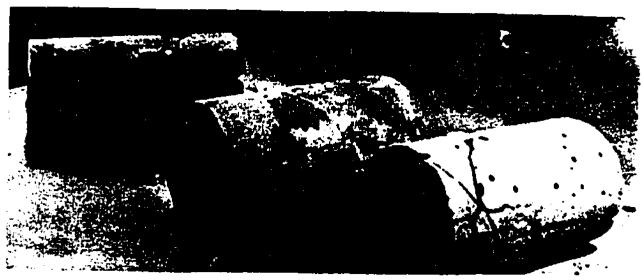
(d) 20% glass aggregate substitute

Figure 31. General fracture behavior of new glass concrete composites at different percentages of aggregate substitute under uniaxial compressive load.

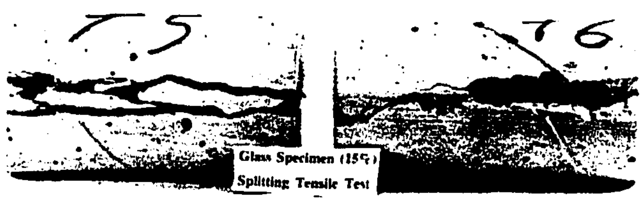
The behavior of glass concrete composites under splitting tensile loads had some differences from the behavior of the plastics concrete composites under the same type of loads. In case of the glass concrete composites, the initial cracks propagated transversely to the direction of the splitting tensile stress and also branched causing a shear fracture mode to be also present. This cracking system can be seen in Figure 32 for all the glass concrete composites at different glass aggregate percentages. It can be seen in this Figure that more area was available to carry the applied splitting tensile loads than that area carried the same type of loads in case of plastics specimens. This enabled the glass concrete composites to arrest more cracks than the plastics concrete composites.before failure. Yet, the failure of the splitting tensile glass specimens was faster and needed a few bridging cracks (due to the decrease of the frequency of crack arrests) than these cracks found in the compressive glass specimens. This was repeatedly observed with all the new glass concrete composites (as well as control and plastics concrete composites) under splitting tensile stress as can be seen in Figure 32. It can also be seen in this figure that the fracture behaviors for all the tested glass splitting tensile specimens are almost identical. This observation coincides with the results obtained from the statistical analysis of the collected data where it was proven that the average (<u>T</u>) values of the glass concrete composites are almost the same in the range of 5 to 20% aggregate substitute. It may also be noticed that the fracture behaviors of 5% and 20% glass specimens are slightly closer to that behavior of the control specimen. On the other hand, the fracture behaviors.of 10% and 15% glass specimens are more closer to these behavior of the plastics specimens. This observation may also enhance the conclusion drawn from the statistical analysis.



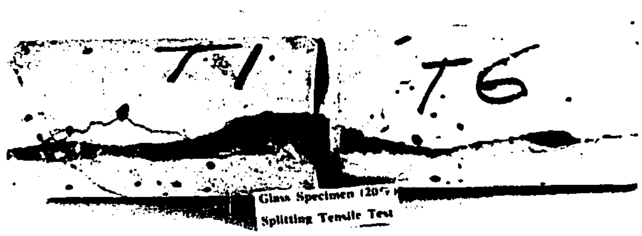
(a) 5% glass aggregate substitute



(b) 10% glass aggregate substitute



(c) 15% glass aggregate substitute



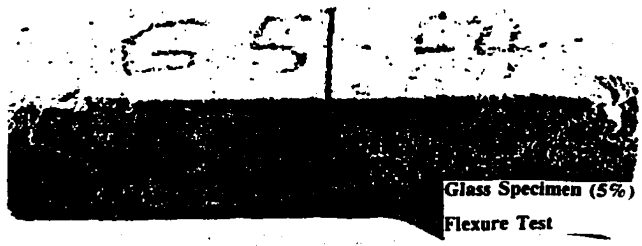
(d) 20% glass aggregate substitute

Figure 32. General fracture behavior of new glass concrete composites at different percentages of aggregate substitute under splitting tensile stress.

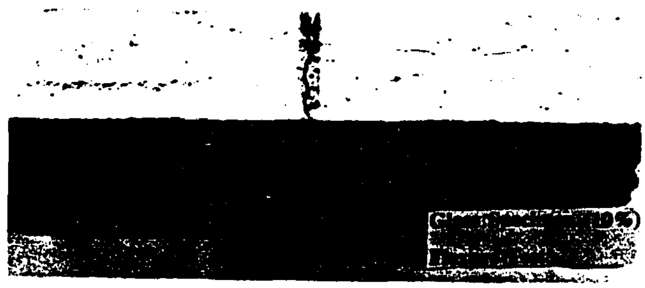
Figure 33 shows the general fracture behavior of the four new glass concrete composites under center-point loading (flexure test). Similar to the behaviors of the control and plastics specimens discussed earlier, almost all the tested flexural specimens experienced In-Plane shear fracture on the upper surface which was in contact with the applied load. However, the side surfaces were fractured at a shear angle ranged from about 0° to 20° to the axial load. This range of shear angles resembles that of control concrete composite mentioned earlier. This means that both the control and glass concrete composites had some characteristics in common. This observation may support the conclusion drawn through statistical analysis for the collected data which suggest that no significant differences between the R value of the control concrete composite and those values of R for the glass concrete composites at different aggregate percentages. The maximum shear angle here resembled the minimum shear angle in case of plastics composites which may indicate that these two different composites had common characteristics at certain aggregate percentages. This observation may be true since it was proven before, from the statistical analysis, that three new concrete composites (containing 5 and 20% glass aggregate as well as 5% plastics aggregate) had higher R values than that of control concrete composite. However, it seems that drawing conclusions or comparing the R and E values of different concrete composites just based on the visual analysis of the photographs showing the fracture behaviors of these composites is not scientifically sound. Generating SEM micrographs for representative samples for these concrete composites may help in relating their general fracture behaviors to their mechanical properties.

Visual Analysis of The New Fiberglass Concrete Composites

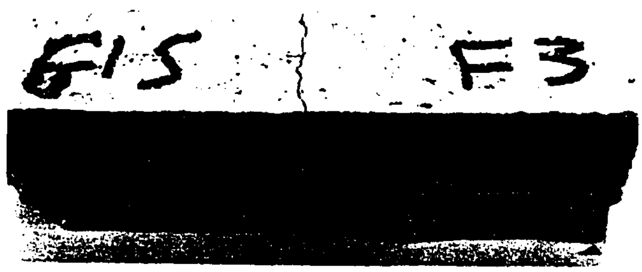
It was shown in Table 6 that, like the glass concrete composites, the overall FM in the case of fiberglass concrete composites decreased with the increase of the fiberglass aggregate substitute percentage. However, it was clear from this table that the reduction rate in the overall FM in the case of fiberglass concrete composites was higher than that of glass concrete composites. This is due to the fact that this fiberglass waste material (FM = 1.6) was considered to be the finest aggregate substitute used in this research study. Based



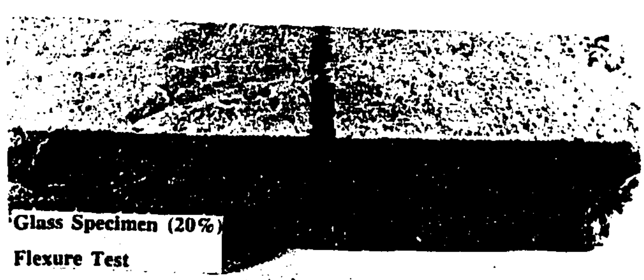
(a) 5% glass aggregate substitute



(b) 10% glass aggregate substitute



(c) 15% glass aggregate substitute



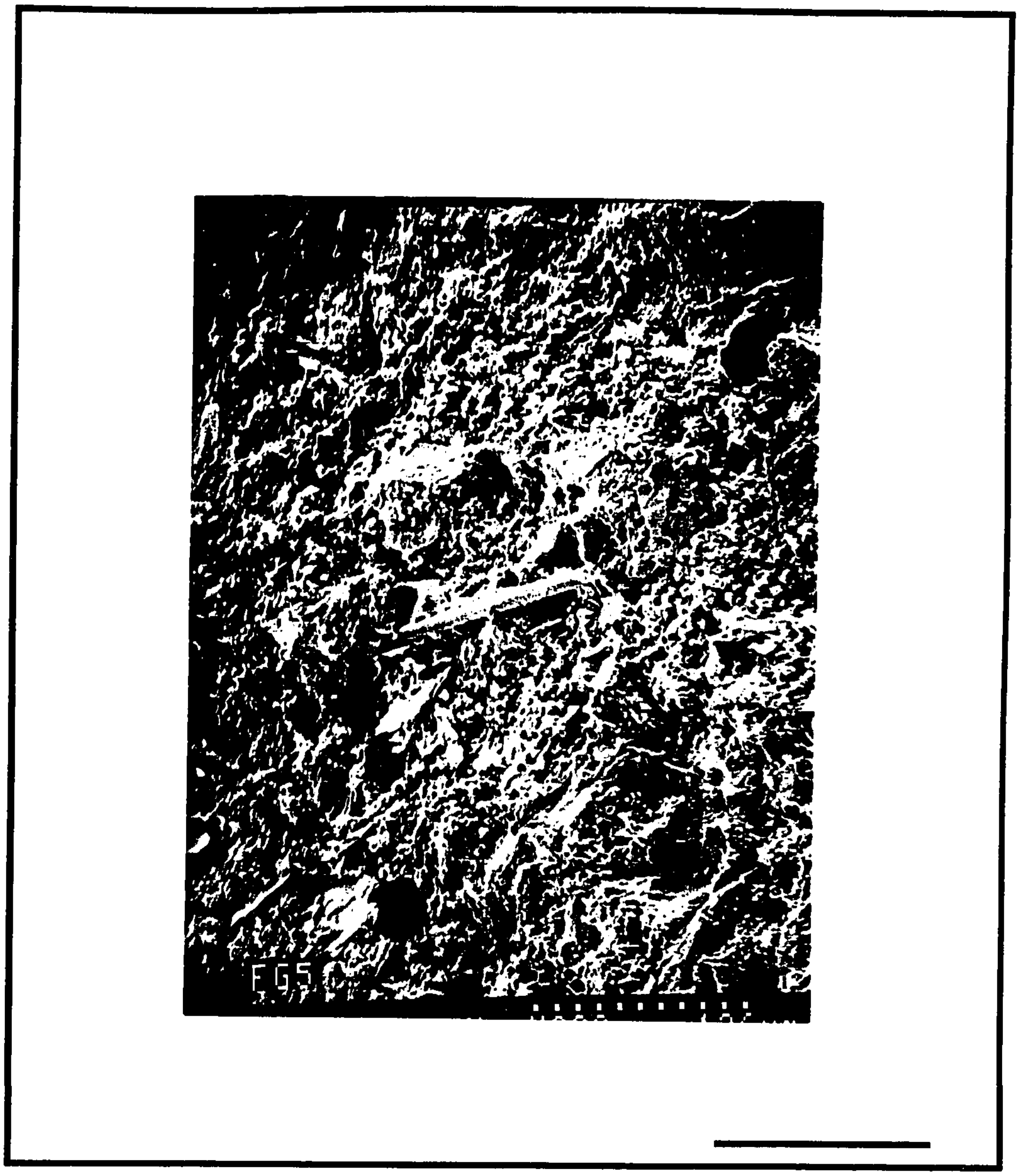
(d) 20% glass aggregate substitute

Figure 33. General fracture behavior of new glass concrete composites at different percentages of aggregate substitute under center-point loading (flexure test).

on the principals of the concrete mix design, this reduction in the overall <u>FM</u> means that these new fiberglass concrete composites had the least amounts of water and gravel while they had the highest amounts of fine aggregates (fiberglass and sand) among the three different types of new concrete composites. Eventually, the continuous reduction of the water content and consequently the water/cement ratio directly affected the porosity in the tz (between the aggregates and the cement paste) and hcp phases and their strengths in these composites. It is to remembered that the main constituents of the fiberglass aggregates were continuous filament fiberglass dispersed in unsaturated polyester base resin (styrene).

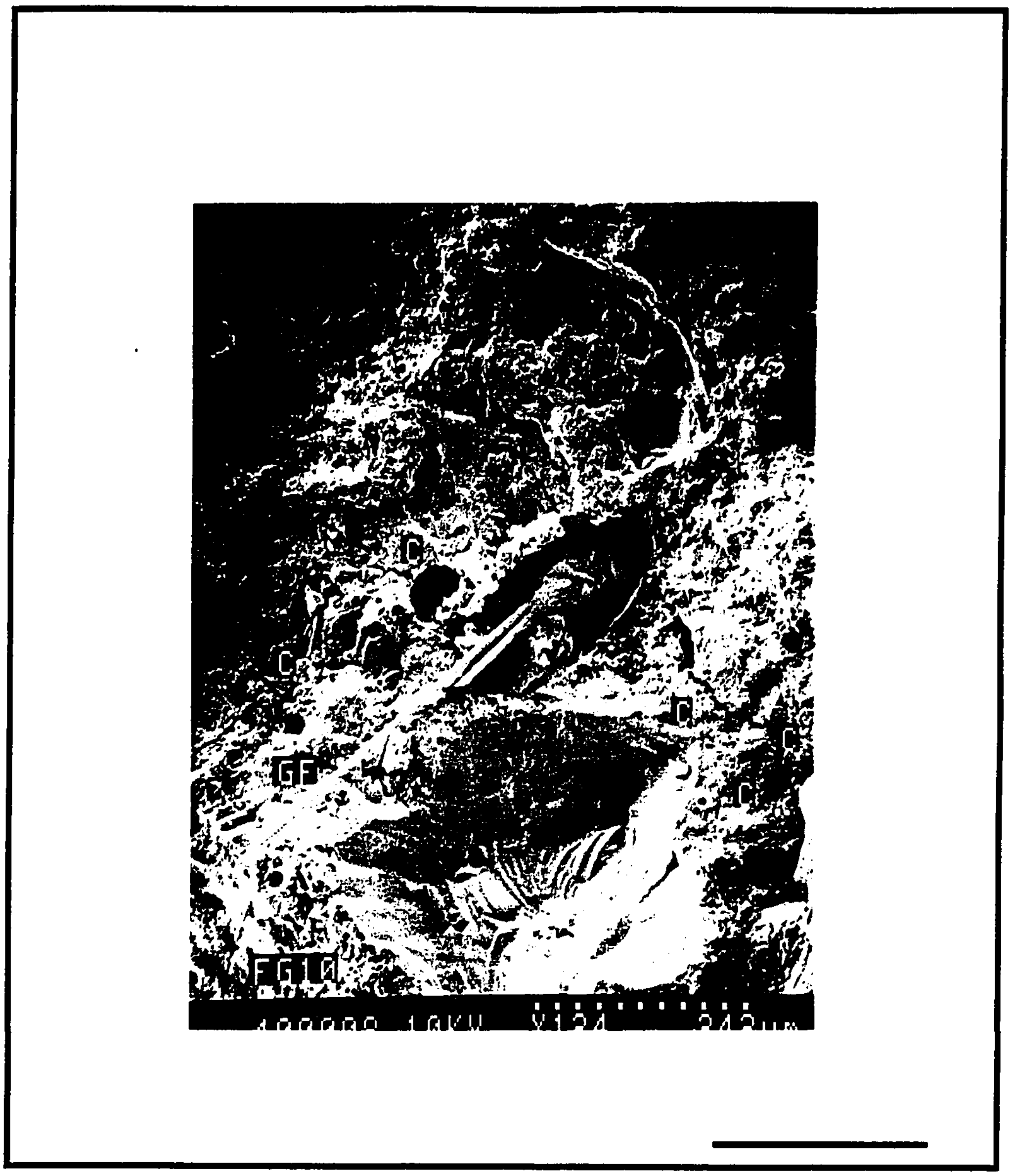
Figures 34 through 37 show the microstructures of the concrete composites containing 5, 10, 15 and 20% fiberglass aggregate substitute at a magnification of X220, X124, X170, and X130 respectively. These Figures show that the glass fiber filaments are randomly distributed in the concrete matrix (see Figures 36 and 37) and their surface remained as smooth as before curing. These glass fibers acted as crack arrestors where the cracks stopped as a result of the resistance of these fibers. It also appears from the Figures that the hydration products growth within the glass fiber filaments provided excessive bonding between fibers and matrix which eliminated fiber pull-out prior to fracture. This can be clearly seen in Figure 37 where the amount of glass fibers is maximum among the four tested concrete composites. It is also noticed that the unsaturated polyester base resin (styrene) had no bonding with the concrete matrix in the transition zone between them. Consequently, the tz phase between the styrene particles and concrete matrix was weak. Also the amounts of the hydration products and styrene particles extremely increased in these concrete composites with the increase of the fiberglass aggregate percentages.

Since the amount of polymers in the fiberglass waste material was higher than that of glass fiber filaments, the strength of the concrete composites depended basically on the tz phase between the concrete matrix and the glass fibers filaments. On the contrary, the hcp and tz (between styrene and concrete matrix) phases were the main sources for failure in these concrete composites. With the increase of the fiberglass aggregate percentage in the concrete composites, the area responsible for strengthening the concrete composites was reduced while the weakening area in these concrete composites was increased. This



X220 10 KV 136 μm

Figure 34. SEM micrograph of a fractured concrete composite containing 5% fiberglass aggregate substitute.

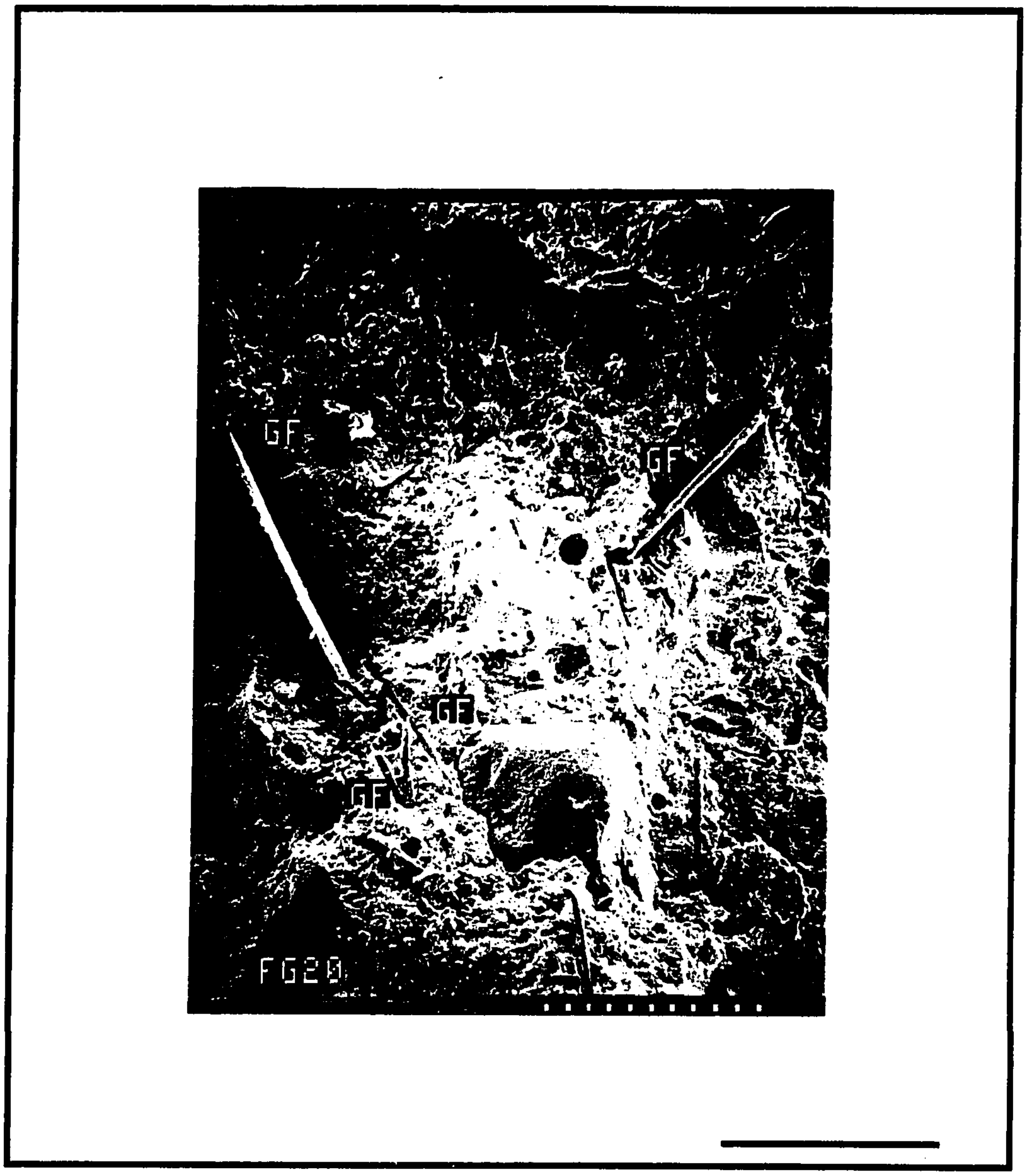


X124 10 KV 242 μm

Figure 35. SEM micrograph of a fractured concrete composite containing 10% fiberglass aggregate substitute.

X170 10 KV 176 μm

Figure 36. SEM micrograph of a fractured concrete composite containing 15% fiberglass aggregate substitute.



X130 10 KV 231 μm

Figure 37. SEM micrograph of a fractured concrete composite containing 20% fiberglass aggregate substitute.

weakening area might have contributed to the continuous reduction of the compressive strength of the new fiberglass concrete composites. This conclusion may be supported by the generated SEM micrographs which show that the presence of microcracks increased with the increase of percentages of fiberglass aggregate.

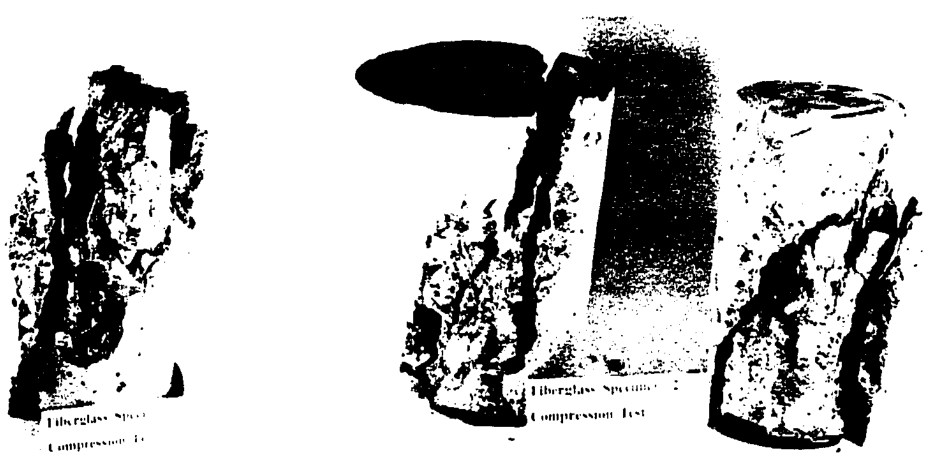
General observation that can be drawn from the SEM micrographs is that up to 10% aggregate substitute materials, the existence of these materials in the concrete composites was scarce. Consequently, no significant differences were expected among all the new composites containing these aggregate substitute materials up to that percentage. This observation is supported by both the statistical and graphical analyses presented before. However, basic and important features of each concrete composite have been clearly shown by using the generated SEM micrographs. Examples are the propagation of the crack through the plastics aggregates which are not bonded with the cement paste; the good interfacial bonding between the cement paste and glass aggregates which acted as crack arrestors preventing crack from propagating through them; the strong bonding between the glass fiber filaments (crack arrestors) and cement paste which is not bonded with the unsaturated polyester base resin (styrene). On the other hand, when higher percentages of aggregate substitutes were added, the SEM micrographs illustrated significant differences among the new concrete composites in terms of the aggregates density and distribution, porosity, hydration products, pull out phenomenon, cracking patterns, and others. Therefore, the SEM micrographs can be used successfully to compare the microstructure of different concrete composites. They can also be used as an indicator to correlate these microstructures of these composites and their mechanical properties.

Figure 38 shows the general fracture behavior of the new fiberglass concrete composites containing 5, 10, 15, and 20% aggregate substitute under uniaxial compression loads. It can be seen in Figures 38a and 38d that the fracture behavior of the 5 and 20% fiberglass concrete composites was of cone and shear mode. On the other hands, the 10 and 15% fiberglass concrete composites experienced pure shear fracture and a combination of columnar and shear fracture modes respectively (see Figures 38b and 38c). Except Figure 38c, all the fracture modes experienced by the 5, 10, 20% fiberglass concrete composites conforms with the fracture types sketched in the ASTM standard (1991b). It is to be noticed that the shape of the fractured fiberglass cylinders is different from that of the fractured plastics cylinders tested under the same loads. However, Figure 38 shows that no microcracks were detected on the outer surfaces of the fiberglass cylinders as those appeared on the plastics cylinders (especially those cylinders at 15 and 20% aggregate substitute). This observation may also suggest that the general fracture behavior of the fiberglass concrete composites is not driven by the glass fiber filament but by the powder unsaturated polyester base resin. In other words, if the plastics fine aggregates are very coarse (their FM is larger than that of sand aggregates), the fracture behavior of the new concrete composites will tend to be of a ductile mode. On the other hand, these concrete composites will show brittle fracture mode if they contain very fine plastics aggregates. It can be also noticed that the appearance of the fiberglass concrete cylinders (which is basically similar to that of glass composites) is different from that of control composite.

Figure 39 shows generated photographs for the general behavior of the fiberglass concrete composites under splitting tensile loads. It is to be noticed that these fractured specimens combine some features shown in the plastics and glass concrete composites tested under the same type of loads. The first feature observed is that the failure of the fiberglass specimens under splitting tensile loads was faster and needed a few bridging cracks (due to the decrease of the frequency of crack arrests) than those cracks found in the compressive fiberglass specimens. This observation was repeatedly shown in all the tested plastics and glass concrete composites under the same type of loads. The second feature observed is that almost all the fractured specimens were easy to handle after testing without damaging their original shape. In other words, the tested fiberglass specimens held their integrity even after testing resembling the behavior of the plastics concrete composites under the same type of loads. This feature was not experienced with the glass concrete specimens. In fact, extra precautions was needed to maintain and preserve the shapes of the fractured glass concrete composites in order to generate the photographs shown before.

The third feature that can be seen in Figure 39 is the fracture modes of each fiberglass concrete composite tested under splitting tensile loads. Figures 39a and 39b

(a) 5% fiberglass aggregate substitute (b) 10% fiberglass aggregate substitute

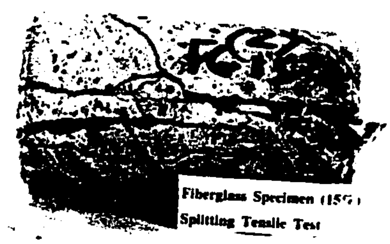


(c) 15% fiberglass aggregate substitute (d) 20% fiberglass aggregate substitute

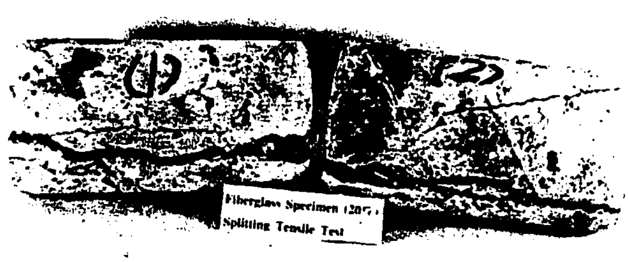
Figure 38. General fracture behavior of new fiberglass concrete composites at different percentages of aggregate substitute under uniaxial compressive load.

(a) 5% fiberglass aggregate substitute

(b) 10% fiberglass aggregate substitute



(c) 15% fiberglass aggregate substitute



(d) 20% fiberglass aggregate substitute

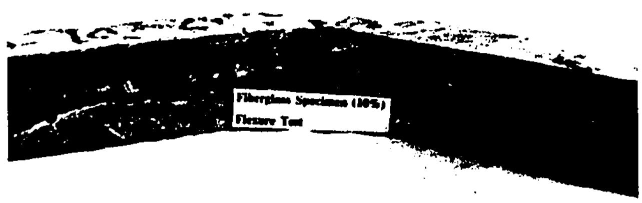
Figure 39. General fracture behavior of new fiberglass concrete composites at different percentages of aggregate substitute under splitting tensile stress.

show that the initial cracks in the 5 and 10% fiberglass concrete composites propagated only transversely to the direction of the splitting tensile stress. This behavior resembles that of the plastics concrete composites. On the other hand, Figures 39c and 39d show that the initial cracks in the 15 and 20% fiberglass concrete composites propagated transversely to the direction of the splitting tensile stress and also branched causing a shear fracture mode to be also present. This cracking system is also experienced by the glass concrete composites. This means that more area was available (in case of 15 and 20% fiberglass concrete specimens) to carry the applied splitting tensile loads than that area which carried the same type of loads in case of 5 and 10% fiberglass concrete specimens. This enabled the 15 and 20% fiberglass (as well as all the glass) concrete composites to arrest more cracks than the plastics concrete composites before failure. However, the collected data showed that the $\underline{T}$ values for the 15 and 20% fiberglass concrete composites were smaller than those for 5 and 10% fiberglass concrete composites. This observation and conclusion contradicts the conclusion drawn from the visual analysis conducted to compare the behaviors of the glass and plastics concrete composites and relate their general fracture behavior to their $\underline{T}$ values. This contradiction simply suggests that relating the general fracture behavior of concrete composites to their mechanical properties should be only on qualitative base which may be scientifically valid.

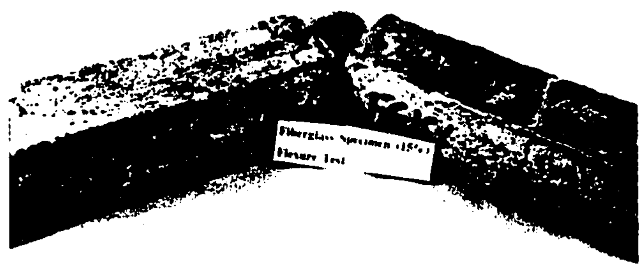
As a conclusion for the visual analysis of the general fracture behavior of the tested splitting tensile specimens, there are similarities and slight differences among all the three different types of concrete composites (plastics, fiberglass, and glass). In more details, the general fracture behavior of all the tested plastics concrete specimens at different percentages of aggregate substitute was basically the same. The same conclusion can also be drawn for the fracture behavior of all the glass concrete specimens. In the case of fiberglass concrete specimens, the fracture behavior of these specimens was a combination between the behavior of plastics and glass concrete specimens. In addition, the majority of the splitting tensile concrete composites fractured in a different fashion than that of the control specimen. These conclusions match those resulted from the statistical and graphical analyses to a great extent. Based on the present research, it is believed that the visual analysis technique should be strongly recommended to compare the properties of different types of concrete composites qualitatively. This technique may be also used to predict whether different concrete composites have the same brittle or ductile fracture modes under splitting tensile loads.

The general fracture behavior of the four new fiberglass concrete composites under center-point loading (flexure test) is shown in Figure 40. It is noticed that the general behavior of these tested fiberglass flexural specimens is basically the same as those behaviors of the control, plastics, and glass specimens. Almost all the tested flexural specimens experienced In-Plane shear fracture on the upper surface which was in contact with the applied load. However, the side surfaces were fractured at a shear angle ranged from about 5° to 35° to the axial load. This range of shear angles may approach the lower and upper limits for the other concrete composites (0°-20° for glass and control concrete specimens and 20°-30° for the plastics specimens). This means that there is something in common among all the control and new concrete composites. This observation may support some of the conclusions drawn through statistical and graphical analyses for the collected data which suggest that no significant differences among the R and E values of the control and new concrete composites at certain aggregate percentages (such as 5%). However, it is difficult to draw general conclusions or to compare the R and E values of different concrete composites just based on the visual analysis of the photographs showing the fracture behaviors of these composites. Once more, generating SEM micrographs for representative samples for these concrete composites may help in relating their general fracture behaviors and their mechanical properties.

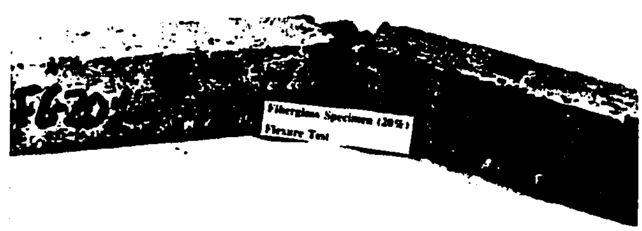
(a) 5% fiberglass aggregate substitute



(b) 10% fiberglass aggregate substitute



(c) 15% fiberglass aggregate substitute



(d) 20% fiberglass aggregate substitute

Figure 40. General fracture behavior of new fiberglass concrete composites at different percentages of aggregate substitute under center-point loading (flexure test).

CHAPTER V

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Summary

The problem of disposing and managing solid waste materials in the United States and other industrial countries has become one of the major environmental, economical and social issues. According to most experts in the U.S., an integrated waste management approach (involving source reduction, reuse, recycling, landfilling and incineration) should be implemented to control the increasing waste disposal problems. The three main methods to handle the MSW in the U.S. are landfilling, incineration, and recycling. Since the first two options are not viable in the long run, recycling is the most promising solution to the disposal materials in the waste stream. Recycling can be very powerful if some of the associated problems such as collecting and sorting the waste materials; processing such used materials into useful products; and most importantly marketing the recycled products can be solved. One of the most promising markets to utilize recycled waste materials successfully on an open-loop basis is the construction industry.

The purpose of this research study was to evaluate the possibility of using different granulated solid waste materials (plastics, fiberglass, and glass) from different sources as partial aggregate substitutes to the fine aggregate (sand) in the portland cement concrete mixture to produce new concrete composites. Twelve research questions were structured to establish quantitative and qualitative engineering information about these new concrete composites. The first six research questions were quantitative type of questions concerning some of the mechanical properties of the developed cementitious concrete composites. On the other hand, the other six research questions were qualitative type of questions concerning the microstructure and the general fracture behaviors of the developed concrete composites and their relationships with the obtained mechanical properties for these composites. Therefore, three different types of concrete composites were prepared containing one of the aggregate waste materials. Each type of these composites contained one of four different volume percentages of aggregate substitute (5, 10, 15, and 20%). A control cementitious concrete composite was also prepared as a reference for the new concrete composites. Three different test methods were conducted on these cementitious concrete composites: compression strength test, splitting tensile strength test, and flexure test. Five specimens were tested in the case of compression and flexural tests while six specimens were tested in the case of splitting tensile test for each concrete composite.

Upon completing the mechanical testing, quantitative analysis of the data was conducted in order to determine and characterize the four mechanical properties under consideration in this research study. These properties were: compressive strength, splitting tensile strength, modulus of rupture, and flexural modulus of elasticity. Statistical and graphical analyses were performed on the measured values of the mechanical properties for both the control and new concrete composites. Three methods and tests of statistical analysis were used to compare and discuss the recorded data. The first statistical analysis method was a two-way factor using the percentage and type of aggregate substitute as a two-way analysis of variance (Two-Way ANOVA). This method was used to determine whether the types and percentages of aggregate substitutes as well as their interactions have any significant effects on each of the mechanical properties of the new cementitious concrete composites. The second statistical analysis method was the one-way analysis of variance (One-Way ANOVA). This method was basically used to determine whether there were significant differences among the values of the mechanical properties of the control concrete composite and those values for the new concrete composites containing different percentages of aggregate substitutes. Finally, an appropriate post hoc test (Tukey HSD procedure) was used to identify any significant differences among the control and new concrete composites containing different percentages of aggregate substitutes. In addition, graphical representation and analysis for the obtained results were also included to compare the developed cementitious concrete composites with the control concrete composite.

In addition to the above quantitative analyses, a qualitative analysis was conducted on the developed concrete composites to answer the second six research questions. These questions dealt with the microstructure and the general fracture behaviors of the developed concrete composites and their relationships with the obtained mechanical properties for these composites. In order to do so, visual analysis was conducted to generated photographs in order to study the general fracture behavior of the control and new concrete composites. A scanning electron microscope was also used to produce SEM micrographs. The following reasons were behind using SEM: (a) to visually analyze the morphology of the fine aggregates used in this research before and after mixing them with the other concrete ingredients; (b) to study the microstructure of, and the interfacial bonding between the used aggregates and cementitious matrix in the control and new concrete composites at different aggregate percentages through the visual analysis of the SEM micrographs; and (c) to visually analyze the crack behavior of each of the tested concrete composites and observe any effects of the types and percentages of aggregates on the features of the cracking systems in these composites.

Conclusions

The following conclusions were based on the twelve research hypotheses (mentioned in chapter I) and the statistical, graphical, and visual analyses of the obtained results presented in chapter IV. Therefore, each research hypothesis was restated and completed with an appropriate descriptive explanation of the findings and then a general conclusion concerning this research hypothesis was made.

Research Hypothesis 1

It is hypothesized that there will be a difference between the average values of the mechanical properties (compressive, flexural, and splitting tensile strengths as well as flexural modulus of elasticity) of the developed concrete composites using different percentages of plastics aggregate substitute (5, 10, 15, and 20%) added to these composites

Compressive strength. Results obtained from the compression testing of the control and plastics concrete composites showed that the average calculated compressive strength (f'_c) of the control concrete composite was 5334 psi. On the other hand, the average (f'_c) for the 5% plastics concrete composite was 4416 psi. This value of (f'_c) was 17% lower than its counterpart for the control concrete composite. The average (f'_c) values for the 10 and 15% plastics concrete composite were 3864 and 3284 psi respectively. These values of (f'_c) were 28% and 38% lower than their counterpart of the obtained control concrete composite. Finally for 20% plastics concrete composite, the average (f'_c)

value was 4090 psi. This value of (f'_c) was 23% lower than that of the obtained control concrete composite.

When statistical analysis methods were applied to the average values of (f'_c) of the control and new concrete composites, it was found that at .05 level of significant (95 percent level of confidence), there were significant differences between the (f'_c) value of the control concrete composite and those values for the new concrete composites containing 5 to 20% plastics aggregate substitutes. The same results were obtained when graphical representation and analysis was applied to the same set of data. Therefore, it can be concluded that research hypothesis 1 is supported while the null hypothesis 1 is rejected in terms of the (f'_c) property.

Splitting tensile strength. Results obtained from the splitting tensile testing of the control and plastics concrete composites showed that the average calculated splitting tensile strength (T) of the control concrete composite was 563 psi. On the other hand, the average (T) values for the 5 and 10% plastics concrete composites were 438 and 428 psi respectively. These values of (T) were 22 and 24% lower than their counterpart for the control concrete composite. Finally, the average (T) value for the 15 and 20% plastics concrete composite were 448 and 438 psi respectively. These values of (T) were 20 and 22% lower than their counterpart of the obtained control concrete composite.

Results obtained from applying statistical analysis methods to the average values of (T) for the control and new concrete composites show that at .05 level of significant, there were significant differences between the (T) value of the control concrete composite and those values for the new concrete composites containing 5, 10, 15, and 20% plastics aggregate substitutes. The same results were obtained when graphical representation and analysis was applied to the same set of data. Therefore, it can be concluded that research hypothesis 1 is supported while the null hypothesis 1 is rejected in terms of the T property.

Modulus of rupture. Results obtained from the flexure testing of the control and plastics concrete composites showed that the average calculated modulus of rupture (R) of the control concrete composite was 878 psi. On the other hand, the average (R) value for the 5% plastics concrete composite was 944 psi. This value of (R) was 7% higher than its counterpart for the control concrete composite. The average (R) values for the 10 and 15% plastics concrete composite were 801 and 650 psi respectively. These values of (R) were 9 and 26% lower than their counterpart of the obtained control concrete composite. Finally for 20% plastics concrete composite, the average (R) was 635 psi. This value of (R) was 28% lower than that of the obtained control concrete composite.

When statistical analysis methods were applied to the average values of (R) of the control and new concrete composites, it was found that at .05 level of significant (95 percent level of confidence), there were no significant differences between the (R) value of the control concrete composite and those values for the new concrete composites containing 5 and 10% plastics aggregate substitutes. On the other hand, it was also found that there were significant differences between the (R) value of the control concrete composite and those values for the new 15 and 20% plastics concrete composites. The same results were obtained when graphical representation and analysis was applied to the same set of data. Therefore, it can be concluded that research hypothesis 1 is only supported above 10% plastics aggregate substitute while the null hypothesis 1 is rejected above the same percentage in terms of the (R) property.

Flexure modulus of elasticity. The results obtained from the flexure testing of the control and plastics concrete composites showed that the average calculated flexure modulus of elasticity (E) of the control concrete composite was 67.31 Ksi. On the other hand, the average (E) values for the 5 and 10% plastics concrete composites were 99.40 and 70.65 Ksi respectively. These (E) values were 48 and 5% higher than their counterpart for the control concrete composite respectively. The average (E) values for the 15 and 20% plastics concrete composites were 62.35 and 61.82 Ksi respectively. These values of (E) were 7 and 8% lower than their counterpart of the obtained control concrete composite.

When statistical analysis methods were applied to the average values of (E) of the developed concrete composites, it was found that at .05 level of significant, there were no significant differences between the (E) value of the control concrete composite and those values for the new concrete composites containing 5, 10, 15, and 20% plastics aggregate substitutes. The same results were obtained when graphical representation and analysis was applied to the same set of data except in the case of 5% plastics concrete composite which is significantly different than that of control concrete composite. Therefore, it can be concluded that research hypothesis 1 is not generally supported while the null hypothesis 1 is generally supported in terms of the (E) property.

Conclusions. Based on the statistical and graphical analyses of the results for all the four mechanical properties considered in the present research study, the following conclusions can be reported for the research hypothesis 1:

1. The average values of the compressive and splitting tensile strengths of the new concrete composites containing 5, 10, 15, and 20% plastics aggregate substitute were significantly different from those average values of the control concrete composite.

2. Compared to the flexure strength of the control concrete composite, the 5 and 10% plastics concrete composites were the same while the 15 and 20% plastics concrete composites were significantly different from that of control concrete composite.

3. Compared to the modulus of elasticity of the control concrete composite, the 10, 15 and 20% plastics concrete composites were almost the same while the 5% plastics concrete composite was significantly different from that of control concrete composite.

4. In general, adding more volume percentage of plastics aggregate substitute to the cementitious concrete composite led to a reduction in the compressive, splitting tensile, and flexural strengths while the stiffness of that composite was almost constant.

Research Hypothesis 2

It is hypothesized that there will be a difference between the average values of the mechanical properties (compressive, flexural, and splitting tensile strengths as well as flexural modulus of elasticity) of the developed concrete composites using different percentages of glass aggregate substitute (5, 10, 15, and 20) added to these composites and those average values of the control concrete composites.

Compressive strength. The results obtained from the compression testing of the control and glass-containing concrete composites showed that the average (f'_c) values of the control and 5% glass concrete composites were 5334 and 4300 psi respectively. The value of ($\underline{f'_c}$) for the 5% glass concrete composite was 19% lower than its counterpart for the control composite. The average ($\underline{f'_c}$) values for the 10 and 15, and 20% glass concrete composite were 4084, 4046, and 5040 psi respectively. These values of ($\underline{f'_c}$) were 23, 24, and just 5% lower than their counterpart of the obtained control concrete composite.

When statistical analysis methods were applied to the average values of ($\underline{f'_c}$) of the control and new concrete composites, it was found that at .05 level of significant, there were significant differences between the ($\underline{f'_c}$) value of the control concrete composite and those values for the new concrete composites containing 5, 10, and 15% glass aggregate substitutes. On the other hand, no significant differences between the ($\underline{f'_c}$) values of the control and 20% glass concrete composites were identified. The same results were obtained when graphical representation and analysis was applied to the same set of data. Therefore, it can be generally concluded that research hypothesis 2 is supported while the null hypothesis 2 is rejected in terms of the ($\underline{f'_c}$) property.

Splitting tensile strength. The results obtained from the splitting tensile testing of the control and glass concrete composites showed that the average calculated ($\underline{T}$) value of the control concrete composite was 565 psi. On the other hand, the average ($\underline{T}$) values for the 5, 10, 15 and 20% glass concrete composites were 495, 481, 434, and 487 psi respectively. These values of ($\underline{T}$) were 12, 15, 23 and 14% lower than their counterpart for the control concrete composite.

The results obtained from applying statistical analysis methods to the average values of ($\underline{T}$) for the control and new concrete composites show that at .05 level of significant, there were significant differences between the ($\underline{T}$) values of the control, 10% glass, and 15% glass concrete composites. On the other hand, no significant differences between the ($\underline{T}$) values of the control, 5% glass, and 20% glass concrete composites. The same results were obtained when graphical representation and analysis was applied to the same set of data. Therefore, it can be concluded that research hypothesis 2 is partially supported (in cases of 10 and 15% glass aggregate substitute) while null hypothesis 2 is rejected only at the same percentages in terms of the (T) property.

Modulus of rupture. The results obtained from the flexure testing of the control and glass concrete composites showed that the average (R) value of the control concrete composite was 878 psi. On the other hand, the average (R) value for the 5% glass concrete composite was 909 psi. This value of (R) was about 3% higher than its counterpart for the control concrete composite. The average (R) value for the 10% glass concrete composite were 874 psi. This value of (R) was almost identical to that value for the control concrete composite. The average R value for the 15% glass concrete composite were 822 psi. This value of (R) was 7% lower than its counterpart for the control concrete composite. Finally for 20% glass concrete composite, the average (R) was 912 psi. This value of R is similar to the obtained value for the concrete composites containing 5% glass waste aggregate.

When statistical analysis methods were applied to the average values of (R) of the control and new concrete composites, it was found that at .05 level of significant (95 percent level of confidence), there were no significant differences between the (R) value of the control concrete composite and those values for the new concrete composites containing 5, 10, 15, and 20% glass aggregate substitutes. The same results were obtained when graphical representation and analysis was applied to the same set of data. Therefore, it can be concluded that research hypothesis 2 is not supported while the null hypothesis 2 is not rejected in terms of the (R) property.

Flexure modulus of elasticity. The results obtained from the flexure testing of the control and glass concrete composites showed that the average calculated (E) values for the control and 5% glass concrete composites were 67.31 and 71.65 Ksi. This (E) value for the 5% glass concrete composite was 6% higher than its counterpart for the control concrete composite. On the other hand, the average (E) value for the 10% glass concrete composite was 62.54 Ksi. This (E) value was 7% lower than its counterpart for the control concrete composite. The average (E) values for the 15 and 20% glass concrete composites were

82.19 Ksi and 90.57 Ksi respectively. These values of (E) were 22% and 35% higher than their counterpart of the obtained control concrete composite.

When statistical analysis methods were applied to the average values of (E) of the control and new concrete composites, it was found that at .05 level of significant (95 percent level of confidence), there were no significant differences between the (E) value of the control concrete composite and those values for the new concrete composites containing 5, 10, 15, and 20% glass aggregate substitute. The same results were obtained when graphical representation and analysis was applied to the same set of data. Therefore, it can be concluded that research hypothesis 2 is rejected while the null hypothesis 2 is supported in terms of the (E) property.

Conclusions. Based on the statistical and graphical analyses for the obtained results for all the four mechanical properties considered in the present research study, the following conclusions can be reported for the research hypothesis 2:

1. Compared to the compressive strength of the control concrete composite, the f'c values of the 5, 10 and 15% glass concrete composites were significantly different from that of control concrete composite. On the other hand, the f'c values of the control and 20% glass concrete composites were almost the same.

2. The average values of the splitting tensile strength of the new concrete composites containing 10 and 15% glass aggregate substitute were significantly different from those average values of the control concrete composite. On the other hand, the T values of the control, 5 and 20% glass concrete composites were almost the same.

3. Compared to the R and E values of the control concrete composite, all the new tested glass concrete composites were same as those of control concrete composite.

4. In general, adding more volume percentage of glass aggregate substitute to the cementitious concrete composite led to improving the compressive, splitting tensile, and flexural strengths as well as the stiffness of the cementitious concrete composite. It will be of interest to study the effect of adding more glass waste material on the mechanical properties of cementitious concrete composite.

Research Hypothesis 3

It is hypothesized that there will be a difference between the average values of the mechanical properties (compressive, flexural, and splitting tensile strengths as well as flexural modulus of elasticity) of the developed concrete composites using different percentages of fiberglass aggregate substitute (5, 10, 15, and 20%) added to these composites and those average values of the controlled concrete composites.

Compressive strength. Results obtained from the compression testing of the control and fiberglass concrete composites showed that the average calculated (f'_c) value of the control concrete composite was 5334 psi. On the other hand, the average (f'_c) values for the 5, 10, 15, and 20% fiberglass concrete composites were 4452, 4016, 3798 and 3200 psi. These values of (f'_c) were 17, 25, 29, and 40% lower than their counterpart for the control concrete composite.

When statistical analysis methods were applied to the average values of f'_c values of the developed concrete composites, it was found that at .05 level of significant, there were significant differences between the (f'_c) value of the control concrete composite and those values for the new concrete composites containing 5, 10, 15, and 20% fiberglass aggregate substitutes. Same results were obtained when graphical representation and analysis was applied to the same set of data. Therefore, it can be concluded that research hypothesis 3 is supported while the null hypothesis 3 is rejected in terms of the (f'_c) property.

Splitting tensile strength. The results obtained from the splitting tensile testing of the control and fiberglass concrete composites showed that the average calculated (T) value of the control concrete composite was 565 psi. On the other hand, the average (T) values for the 5 and 10% fiberglass concrete composites were 495 and 502 psi respectively. Both these (T) values were about 12% lower than their counterpart for the control concrete composite. Finally, the average (T) values for the 15 and 20% fiberglass concrete composites were 478 and 468 psi respectively. These values of (T) were 15 and 17% lower than their counterpart of the obtained control concrete composite.

Results obtained from applying statistical analysis methods to the average values of (T) for the control and new concrete composites show that at .05 level of significant, there were no significant differences between the (T) value of the control concrete composite and those values for the new concrete composites containing 5, 10, and 15% fiberglass aggregate substitutes. On the other hand, significant differences were identified between the (T) values of the control and 20% fiberglass concrete composite. Same results were obtained when graphical representation and analysis was applied to the same sets of data except that no significant difference between the T values of the control and 20% fiberglass concrete composites can be observed. Therefore, it can be concluded that research hypothesis 3 is rejected while null hypothesis 3 is supported in terms of the (T) property.

Modulus of rupture. The results obtained from the flexure testing of the control and fiberglass concrete composites showed that the average (R) value for the control concrete composite was 878 psi. On the other hand, the average (R) values for the 5, 10, 15, and 20% fiberglass concrete composites were 819, 805, 744, and 762 psi respectively. These (R) values were 7, 9, 15, and 14% lower than their counterpart for the control composite.

When statistical analysis methods were applied to the average values of (R) of the control and new concrete composites, it was found that at .05 level of significant, there were no significant differences between the (R) value of the control concrete composite and those values for the new concrete composites containing 5 and 10% fiberglass aggregate substitutes. On the other hand, significant differences were identified between the (R) value of the control concrete composite and those values for the new concrete composites containing 15 and 20% fiberglass aggregate substitutes. The same results were obtained when graphical representation and analysis was applied to the same set of data. Therefore, it can be concluded that research hypothesis 3 is partially supported (in cases of 15 and 20% fiberglass aggregate substitute) while null hypothesis 3 is only rejected at the same percentages in terms of the (R) property.

Flexure modulus of elasticity. Results obtained from the flexure testing of the control and fiberglass concrete composites showed that the average (E) value of the control concrete composite was 67.31 Ksi. In addition, the average (E) values for the 5, 10, 15, and 20% fiberglass concrete composites were 81.60, 90.93, 90.86, and 81.81 Ksi respectively. These values of (E) were 21, 35, 35, and 22% higher than their counterpart for the control concrete composite.

When statistical analysis methods were applied to the average values of (E) of the control and new concrete composites, it was found that at .05 level of significant, there were no significant differences between the (E) value of the control concrete composite and those values for the new concrete composites containing 5, 10, 15, and 20% fiberglass aggregate substitute. The same results were obtained when graphical representation and analysis was applied to the same set of data. Therefore, it can be concluded that research hypothesis 3 is rejected while the null hypothesis 3 is supported in terms of the E property.

Conclusions. Based on the statistical and graphical analyses for the obtained results for all the four mechanical properties considered in the present research study, the following conclusions can be reported for the research hypothesis 3:

1. The average (f'c) values of the new concrete composites containing 5, 10, 15, and 20% fiberglass aggregate substitute were significantly different from that average value of the control concrete composite especially when more volume percentages were added.

2. All the (T) values of the 5, 10, 15 and 20% fiberglass concrete composites were almost the same as that of the control concrete composite.

3. The R values of the 5 and 10% fiberglass concrete composites were almost the same as that of the control concrete composite. On the other hand, the (R) values of the 15 and 20% fiberglass concrete composites were significantly different from that value of the control concrete composite.

4. All the (E) values of the new tested fiberglass concrete composites were at least as stiff as (or stiffer than) that of the control concrete composite.

5. In general, adding more volume percentages of fiberglass aggregate substitute to the cementitious concrete composite led to reducing the compressive, splitting tensile, and flexural strengths of the cementitious concrete composite. On the other hand, adding more

volume percentage of fiberglass aggregate substitute to the cementitious concrete composite led to the increase in the stiffness of the cementitious concrete composite.

Research Hypothesis 4

It is hypothesized that there will be a difference between the average values of the compressive, splitting tensile, and flexural strengths as well as flexural modulus of elasticity of the developed concrete composites using 5, 10, 15, and 20% of plastics aggregate substitute added to these composites and those average values of the new concrete composites using the same percentages of glass aggregate substitute.

Compressive strength. The results obtained from the compression testing of the plastics and glass concrete composites showed that the average (f'_c) value of the 5% plastics concrete composite was 4416 psi. On the other hand, the average (f'_c) for the 5% glass concrete composite was 4300 psi. This value of (f'_c) was 3% lower than its counterpart for the plastics concrete composite. The average (f'_c) values for the 10, 15, and 20% plastics concrete composite were 3864, 3284, 4090 psi respectively. On the other hand, the average (f'_c) values for the 10, 15, and 20% glass concrete composite were 4084, 4046, 5040 psi respectively. These values of (f'_c) were 6, 23, and 23% higher than their counterparts of the obtained plastics concrete composites.

When statistical analysis methods were applied to the average (f'_c) values for the developed concrete composites, it was found that at .05 level of significant, there were no significant differences between the (f'_c) values of the plastics and glass concrete composites up to 15% aggregate waste substitutes. However, significant differences were identified between the (f'_c) values of the 20% plastics and 20% glass concrete composites. The same results were obtained when graphical representation and analysis was applied to the same set of data except that there was a significant difference identified between the (f'_c) values of the plastics and glass concrete composites at 15% aggregate waste substitutes. This observation is also supported by the above comparison where the (f'_c) values for the 15 and 20% glass concrete composite were 23% higher than their counterparts of the plastics concrete composites. Therefore, it can be concluded that research hypothesis 4 is partially supported (especially above 10% aggregate substitute) while the null hypothesis 4 is only rejected above 10% aggregate substitute in terms of the (f'c) property.

Splitting tensile strength. The results obtained from the splitting tensile testing of the plastics and glass concrete composites showed that the average calculated (T) values for the 5 and 10% plastics concrete composites were 438 psi and 428 psi respectively. On the other hand, the average (T) values for the 5 and 10% glass concrete composites were 495 psi and 481 psi. These values of (T) were about 12% higher than their counterparts for plastics concrete composites. The average (T) values for the 15% plastics and glass concrete composites were 448 psi and 434 psi respectively. This (T) value for the glass concrete composite was 3% lower than its counterpart for the plastics concrete composite. Finally, the average (T) values for the 20% plastics and glass concrete composites were 438 psi and 487 psi respectively. This (T) value for the glass concrete composite was 11% higher than its counterpart for the plastics concrete composite.

The results obtained from applying statistical analysis methods to the average values of (T) for the developed concrete composites show that at .05 level of significant, there were no significant differences between the (T) values for the plastics concrete composites at different percentages of aggregate substitute and their counterparts for the glass concrete composites. Same results were obtained when graphical representation and analysis was applied to the same sets of data. Therefore, it can be concluded that research hypothesis 4 is rejected while null hypothesis 4 is supported in terms of the (T) property.

Modulus of rupture. The results obtained from the flexure testing of the glass and plastics concrete composites showed that the average calculated (R) value for the 5% plastics concrete composite was 944 psi. On the other hand, the average (R) value for the 5% glass concrete composite was 909 psi. This value of (R) was 4% lower than its counterpart for the plastics concrete composite. The average (R) values for the 10, 15 and 20% plastics concrete composites were 801 psi, 650 psi, and 635 psi respectively. On the other hand, the average (R) values for the 10, 15 and 20% glass concrete composites were

874 psi, 822 psi, and 912 psi respectively. These values of (R) were 9, 26, and 44% higher than their counterparts of the obtained plastics concrete composites.

When statistical analysis methods were applied to the average values of (R) for the developed concrete composites, it was found that at .05 level of significant, there were no significant differences between the R values of the 5 and 10% plastics concrete composites and their counterparts containing glass aggregate substitutes. On the contrary, significant differences were identified between the (R) values for both concrete composites at 15 and 20% aggregate substitutes. Same results were obtained when graphical representation and analysis was applied to the same sets of data. Therefore, it can be concluded that research hypothesis 4 is partially supported above 10% aggregate substitute while the null hypothesis 4 is rejected above the same percentage in terms of the (R) property.

Flexure modulus of elasticity. The results obtained from the flexure testing of the plastics and glass concrete composites showed that the average (E) value for the 5 and 10% plastics concrete composites were 99.40 and 70.65 Ksi respectively. On the other hand, the average (E) values for the 5 and 10% glass concrete composites were 71.65 Ksi and 62.54 Ksi. These (E) values were 28 and 11% lower than their counterparts for the plastics concrete composites. The average (E) values for the 15 and 20% plastics concrete composites were 62.35 Ksi and 61.82 Ksi respectively. On the contrary, the average (E) values for the 15 and 20% glass concrete composites were 82.19 Ksi and 90.57 Ksi respectively. These values of (E) were 32% and 47% higher than their counterparts of the obtained plastics concrete composites.

When statistical analysis methods were applied to the average values of (E) for the developed concrete composites, it was found that at .05 level of significant, there were no significant differences between the (E) values for the 5, 10, and 15% plastics concrete composites and their counterparts for the glass concrete composites containing the same percentages of aggregate substitutes. On the other hand, a significant difference was identified between the (E) value for the 20% plastics concrete composite and its counterpart for the glass concrete composite. Results obtained from the graphical representation and analysis to the same sets of data showed that there were obvious significant differences at least between the (E) values for the 5 and 20% plastics concrete composites and their counterparts for the glass concrete composites containing the same percentages of aggregate substitutes. Therefore, it can be concluded that research hypothesis 4 is partially supported while the null hypothesis 4 is partially rejected in terms of the (E) property.

Conclusions. Based on the statistical and graphical analyses for the obtained results for all the four mechanical properties considered in the present research study, the following conclusions can be reported for the research hypothesis 4:

1. The (f'_c) values for both the new plastics and glass concrete composites were almost the same up to 10% aggregate substitutes. On the other hand, the (f'_c) values of the new glass concrete composites were significantly different from those of the new plastics concrete composites when more than 10% aggregate substitute was added.

2. All the (T) values of the concrete composites containing 5, 10, 15, and 20% plastics aggregate substitute were almost the same as those values of concrete composites containing 5, 10, 15, and 20% glass aggregate substitute.

3. The R values for both the new plastics and glass concrete composites were almost the same up to 10% aggregate substitutes. On the other hand, the (R) values of the new glass concrete composites were significantly different from those of the new plastics concrete composites when more than 10% aggregate substitute was added.

4. The (E) value of the the new tested plastics concrete composite containing 5% aggregate substitute was higher than its counterpart for the glass concrete composite. The stiffness of both concrete composites was almost the same at 10% (and may be 15%) aggregate substitute. On the other hand, the glass concrete composite was more stiffer than the plastics one at higher percentage (specifically at 20%) of aggregate substitute.

5. In general, adding more volume percentage of glass aggregate substitute to the cementitious concrete composite led to improving the compressive, splitting tensile, and flexural strengths as well as the stiffness of the concrete composite rather than adding the same volume percentages of plastics aggregate substitute.

Research Hypothesis 5

It is hypothesized that there will be a difference between the average values of the compressive, splitting tensile, and flexural strengths as well as flexural modulus of elasticity of the developed concrete composites using 5, 10, 15, and 20% of plastics aggregate substitute added to these composites and those average values of the new concrete composites using the same percentages of fiberglass aggregate substitute.

Compressive strength. The results obtained from the compression testing of the plastics and fiberglass concrete composites showed that the average calculated (f'_c) values for the 5, 10, and 15% plastics concrete composites were 4416, 3864, and 3284 psi respectively. On the other hand, the average (f'_c) values for the 5, 10, and 15% fiberglass concrete composites were 4452, 4016, and 3798 psi respectively. These values of (f'_c) were about 1, 4, and 16% higher than their counterparts for the plastics concrete composites. Finally for 20% plastics and fiberglass concrete composites, the average (f'_c) values were 4090 psi and 3204 psi respectively. This value of (f'_c) for the fiberglass concrete composite was 22% lower than that of the obtained plastics concrete composite.

When statistical analysis methods were applied to the average values of (f'_c) of the developed concrete composites, it was found that at .05 level of significant (95 percent level of confidence), there were no significant differences between the (f'_c) values of the plastics and fiberglass concrete composites up to 15% aggregate waste substitutes. On the other hand, there was a significant difference between the (f'_c) values of the plastics and fiberglass concrete composites at 20% aggregate waste substitutes. The same results were obtained when graphical representation and analysis was applied to the same set of data. Therefore, it can be concluded that research hypothesis 5 is only supported at 20% waste aggregate substitute while the null hypothesis 5 is only rejected at the same percentage in terms of the (f'_c) property.

Splitting tensile strength. The results obtained from the splitting tensile testing of the plastics and fiberglass concrete composites showed that the average calculated (T) values for the 5, 10, 15, and 20% plastics concrete composites were 438, 428, 448, and

438 psi respectively. On the other hand, the average (T) values for the 5, 10, 15 and 20% fiberglass concrete composites were 495, 501, 478, and 468 psi. These values of (T) were about 12, 17, 7, and 7% higher than their counterparts for plastics concrete composites.

The results obtained from applying statistical analysis methods to the average values of (T) for the developed concrete composites show that at .05 level of significant, there were no significant differences between the (T) values for the plastics concrete composites at different percentages of aggregate substitute and their counterparts for the fiberglass concrete composites. The same results were obtained when graphical representation and analysis was applied to the same sets of data. Therefore, it can be concluded that research hypothesis 5 is rejected while null hypothesis 5 is supported in terms of the (T) property.

Modulus of rupture. The results obtained from the flexure testing of the fiberglass and plastics concrete composites showed that the average calculated (R) values for the 5% plastics and fiberglass concrete composites were 944 and 819 psi respectively. This value of (R) of the glass concrete composite was 13% lower than its counterpart for the plastics concrete composite. The average (R) values for the 10, 15 and 20% plastics concrete composites were 801, 650, and 635 psi respectively. On the other hand, the average (R) values for the 10, 15 and 20% fiberglass concrete composites were 805 psi, 744 psi, and 762 psi respectively. These values of (R) were 0.5, 14, and 20% higher than their counterparts of the obtained plastics concrete composites.

When statistical analysis methods were applied to the average (R) values for the new concrete composites, it was found that at .05 level of significant, there were no significant differences between the (R) values of the plastics concrete composites containing 5 and 10% plastics aggregate substitutes and those values for their counterparts containing 5 and 10% fiberglass aggregate substitutes. On the contrary, significant differences were identified between the (R) values for both concrete composites at 15 and 20% aggregate substitutes. The same results were obtained when graphical representation and analysis was applied to the same sets of data. Therefore, it can be concluded that research hypothesis 5 is partially supported above 10% aggregate substitute while the null hypothesis 5 is rejected above the same percentage in terms of the (R) property.

Flexure modulus of elasticity. The results obtained from the flexure testing of the plastics and fiberglass concrete composites showed that the average calculated (E) values of the 5% plastics and fiberglass concrete composites were 99.40 and 81.60 Ksi respectively. This value for the fiberglass composite is 18% lower than its counterpart for plastics composite. The average (E) values for the 10, 15 and 20% plastics concrete composites were 70.65, 62.35, and 61.82 Ksi respectively. On the other hand, the average (E) values for the 10, 15 and 20% fiberglass concrete composites were 90.93, 90.26, and 81.81 Ksi respectively. These values of (E) were 29, 45, and 32% higher than their counterparts for plastics concrete composites.

When statistical analysis methods were applied to the average values of (E) for the developed concrete composites, it was found that at .05 level of significant, there were no significant differences between the (E) values for the 5, 10, 15, and 20% plastics concrete composites and their counterparts for the fiberglass concrete composites containing the same percentages of aggregate substitutes. Results obtained from representing the same sets of data graphically and analyzing them showed that there were obvious significant differences at least between the (E) value for the 15% (and may be also the 10 and 20%) plastics concrete composite and its counterpart for the 15% fiberglass concrete composite. Therefore, it can be concluded that research hypothesis 5 is partially supported while the null hypothesis 5 is partially rejected in terms of the (E) property.

Conclusions. Based on the statistical and graphical analyses for the obtained results for all the four mechanical properties considered in the present research study, the following conclusions can be reported for the research hypothesis 5:

1. The (f'_c) values for both the new plastics and fiberglass concrete composites were almost the same up to 15% aggregate substitutes. On the other hand, the (f'_c) value of the new plastics concrete composite was significantly different from (i.e. higher than) that of the new fiberglass concrete composite when 20% aggregate substitute was added.

2. All the (T) values of the concrete composites containing 5, 10, 15, and 20% plastics aggregate substitute were almost the same as those values of concrete composites containing 5, 10, 15, and 20% fiberglass aggregate substitute.

3. The (R) values for both the new plastics and fiberglass concrete composites were almost the same up to 10% aggregate substitutes. On the other hand, the (R) values of the fiberglass concrete composite was significantly different from those of the plastics concrete composites when more than 10% aggregate substitute was added up to 20%.

4. The (E) value of the new 5% plastics concrete composite was higher than its counterpart of the fiberglass concrete composite. On the other hand, the fiberglass concrete composite showed more stiffness than the plastics concrete composite when 10 to 20% aggregate substitutes were used.

5. In general, the fiberglass concrete composites had better (f'c) (except if high percentage of aggregate substitute is added), (T), and (R) values (especially if more than 10% aggregate substitute is added) than the plastics concrete composites. Furthermore, the fiberglass concrete composites were more stiffer than their plastics counterpart especially if 10 to 20% aggregate substitute are used in the cementitious concrete composite.

Research Hypothesis 6

It is hypothesized that there will be a difference between the average values of the compressive, splitting tensile, and flexural strengths as well as flexural modulus of elasticity of the developed concrete composites using 5, 10, 15, and 20% of glass aggregate substitute added to these composites and those average values of the new concrete composites using the same percentages of fiberglass aggregate substitute.

Compressive strength. The results obtained from the compression testing of the glass and fiberglass concrete composites showed that the average (f'c) values for the 5% glass and fiberglass concrete composites were 4300 and 4452 psi respectively. This value of (f'c) for the fiberglass composite was about 4% higher than that of glass composite. On the other hand, the average (f'c) values for the 10, 15, and 20% glass composites were 4084, 4046, and 5040 psi respectively. The average (f'c) values for the 10, 15, and 20% fiberglass concrete composites were 4016, 3798, and 3204 psi respectively. These values of (f'c) were about 2, 6, and 36% lower than their counterparts for the glass concrete composites.

When statistical analysis methods were applied to the average values of (f'c) of the developed concrete composites, it was found that at .05 level of significant, no significant differences between the (f'c) values of the glass and fiberglass concrete composites were found up to 15% aggregate waste substitutes. On the other hand, a significant difference between the f'c values of the glass and fiberglass concrete composites was identified at 20% aggregate waste substitutes. The same results were obtained when graphical representation and analysis was applied to the same set of data except that there was a significant difference identified between the (f'c) values of the fiberglass and glass concrete composites at 15% aggregate waste substitutes. Therefore, it can be concluded that research hypothesis 6 is partially supported (especially above 10% aggregate substitute) while the null hypothesis 6 is only rejected above the same percentage in terms of the (f'c) property.

Splitting tensile strength. The results obtained from the splitting tensile testing of the glass and fiberglass concrete composites showed that the average calculated (T) values for the 5, 10, and 15% glass concrete composites were 495, 481, 434 psi respectively. On the other hand, the average T values for the 5, 10, and 15% fiberglass concrete composites were 495, 501, and 478 psi. These values of (T) were about 0, 4, and 10% higher than their counterparts for glass concrete composites. On the other hand, the average (T) values for the 20% glass and fiberglass concrete composites were 487 and 468 psi. This (T) value of fiberglass was about 4% lower than its counterpart for glass concrete composite.

The results obtained from applying statistical analysis methods to the average values of (T) for the developed concrete composites show that at .05 level of significant, there were no significant differences between the (T) values for the glass concrete composites at different percentages of aggregate substitute and their counterparts for the fiberglass concrete composites. The same results were obtained when graphical representation and analysis was applied to the same sets of data. Therefore, it can be concluded that research hypothesis 6 is rejected while null hypothesis 6 is supported in terms of the (T) property.

Modulus of rupture. The results obtained from the flexure testing of the fiberglass and glass concrete composites showed that the average (R) values for the 5, 10, 15, and 20% glass concrete composites were 909, 874, 822, and 912 psi respectively. On the other hand, the (R) values for the 5, 10, 15, and 20% fiberglass concrete composites were 819, 805, 744, and 762 psi respectively. These values of (R) were 10, 9, 9, and 16% lower than their counterparts of the obtained glass concrete composites.

When statistical analysis methods were applied to the average values of (R) for the developed concrete composites, it was found that at .05 level of significant, there were no significant differences between the (R) values of the glass concrete composites containing 5 and 10% plastics aggregate substitutes and those values for their counterparts containing 5 and 10% fiberglass aggregate substitutes. On the contrary, significant differences were identified between the (R) values for both concrete composites at 15 and 20% aggregate substitutes. The same results were obtained when graphical representation and analysis was applied to the same sets of data. Therefore, it can be concluded that research hypothesis 6 is partially supported above 10% aggregate substitute while the null hypothesis 6 is rejected above the same percentage in terms of the (R) property.

Flexure modulus of elasticity. The results obtained from the flexure testing of the glass and fiberglass concrete composites showed that the average (E) values of the 5, 10, and 15% glass concrete composites were 71.65, 62.54, and 82.19 Ksi respectively. On the other hand, the average (E) values of the fiberglass composites were 81.60, 90.93, and 90.26 Ksi. These values of (E) were 14, 45, and 10% higher than their counterparts for glass composites. The average (E) values for the 20% glass and fiberglass concrete composites were 90.57 and 81.81 Ksi respectively. The (E) value for fiberglass composite was 10% lower than its counterpart for glass concrete composite.

When statistical analysis methods were applied to the average values of (E) for the developed concrete composites, it was found that at .05 level of significant, there were significant differences only between the (E) value for 10% glass concrete composite and its counterpart for the 10% fiberglass concrete composite. The same results were obtained from the graphical representation and analysis to the same sets of data. Therefore, it can be concluded that research hypothesis 6 is only supported when 10% waste aggregate substitute was used while the null hypothesis 6 is only rejected when the same percentage of aggregate substitute was used in terms of the (E) property.

Conclusions. Based on the statistical and graphical analyses for the obtained results for all the four mechanical properties considered in the present research study, the following conclusions can be reported for the research hypothesis 6:

1. The (f'_c) values for both the new glass and fiberglass concrete composites were almost the same up to 10% aggregate substitutes. On the other hand, the (f'_c) values of the new glass concrete composites were significantly different from (i.e. higher than) those of the new fiberglass concrete composites when more than 10% aggregate substitute was added up to 20%.

2. All the (T) values of the concrete composites containing 5, 10, 15, and 20% glass aggregate substitute were almost the same as those values of concrete composites containing 5, 10, 15, and 20% fiberglass aggregate substitute.

3. The (R) values for both the new glass and fiberglass concrete composites were almost the same up to 10% aggregate substitutes. On the other hand, the (R) values of the new glass concrete composite was significantly different from those of the new fiberglass concrete composites when more than 10% aggregate substitute was added up to 20%.

4. The flexure modulus of elasticity of the new fiberglass concrete composite was higher than its counterpart for the glass concrete composite up to 15% aggregate substitute. On the other hand, the glass concrete composite became as stiff as that of fiberglass concrete composite when 20% aggregate substitutes was used.

5. In general, adding more volume percentage of glass aggregate substitute to the cementitious concrete composite led to improving the (f'_c) and (R) values rather than adding the same volume percentages of fiberglass aggregate substitute. On the other hand, the fiberglass concrete composites were more stiffer than their glass counterpart when up to 15% aggregate substitute were used in the concrete composite. Finally, both the glass and fiberglass concrete composites had almost the same (T) values.

Research Hypothesis 7

It is hypothesized that there will be observable differences between the microstructure and interfacial bonding of the developed concrete composites using 5, 10, 15, and 20% of plastics aggregate substitute added to these composites and those of the control concrete composite.

Control concrete composite. The SEM micrographs for a fractured control concrete composite showed that the cracking systems in this control concrete composite occurred in two phases: the hydrated cement paste (hcp) phase and the interfacial region (transition zone, tz) between the aggregates (GR) and the hcp. These cracking systems extended in the tz phase and underneath the GR which were pulled out (upon debonding) from the composite. Finally, some dehydration products in the form of calcium hydroxide (CH) crystals were scattered in the empty grooves (resulted from pulling out the GR), voids, and the surface of hcp.

The general fracture behavior observed (from photographs) in case of compression testing for the control concrete composite was of cone and split shape. It was also noticed that the resulting main cracks along the loading axis separated this specimen into a few chunk pieces. Multi microcracks were also initiated and propagated in the hcp and tz phases causing failure in the control concrete composite. On the other hand, the control concrete composite tested under center-point loading experienced In-Plane shear fracture on the upper surface which was in contact with the applied load. However, the side surfaces of this composite were fractured with a shear angle of about 20° to the axial load. Finally, photographs taken for the control concrete specimens tested under splitting tensile test showed main cracks (due to brittle failure along the axis of the diametral load) which were created to split these specimens into two halves. Some microcracks were also branched from the main cracks causing another main crack across the diameter of the specimen.

Plastics concrete composites. SEM micrographs taken for cementitious concrete composites containing plastics aggregate substitute suggested that failure in these composites occurred in three phases: hcp, tz, and plastics aggregate phases. It was also observed that the cracking systems went through the hcp and propagated through the plastics aggregate causing it to shear. It was noticed that no bonding occurred between the plastic aggregates and the cement paste. This simply means that the plastics aggregate substitute was only used as a filler in all the new concrete composites containing different percentages of plastics aggregates. It was also noticed that the amounts of the CH crystals and plastic particles (scattered in the empty grooves, voids, and the areas of hcp and tz) are more than the amount of CH crystals exited in the control concrete composite. These amounts were increased by the increase of the percentage of plastics aggregate substitute used in concrete composites. Since the new plastics concrete composites had more water and gravel while they were short of sand and plastics, the continuous increase of the water content in these composites and consequently the water/cement ratio directly affected the porosity in the hcp and tz phases and their strengths. It appeared that the weakness in the hcp and the plastics aggregate phases might have contributed to the reduction of the (f'_c) of the new plastics concrete composites. An exception of this conclusion was the sudden increase in the (f'_c) of the 20% plastics concrete composite. That might have happened because of the increase in the amount of plastic aggregates increased the cracking energy required to propagate the initial microcracks causing fracture of the concrete composite (i.e., the plastics aggregates might have increased the resistance of this composite to cracking). In general, the plastic aggregates acted as crack arrestors and energy absorbers in the tested plastics concrete composites.

Photographs taken of the concrete cylinders containing different percentages of plastics aggregate substitute and tested under uniaxial compression loads suggested that the existence of these aggregates was one of the main reasons to hold the shape of these cylinders even after complete failure. It was also noticed that the more the amount of plastics aggregates was used, the more the shape of the fractured plastics concrete intact cylinders was. Slight differences in the fracture behaviors of both the control and 5% plastics concrete cylinders were also observed. On the other hand, the general fracture behaviors for all the tested splitting tensile specimens containing different percentages of plastics aggregate substitute were almost identical. This observation coincided with the results obtained from the statistical analysis of the collected data. Furthermore, from the statistical analysis, the conclusion that all the (T) values obtained for the new plastics composites were less than that of the control concrete composite may also be supported by the visual analysis of the obtained photographs for the general fracture behaviors of these composites. Since the plastics specimens had weaker phases and more initial microcracks than those phases and initial microcracks in the control composite, the crack propagation in the plastics concrete composites was faster than that in the control composite. This resulted in more than one main crack (which was observed in the control specimen) to be seen in the plastics concrete specimens. Unlike the control specimen, the majority of the plastics concrete specimens tested under splitting tensile stress experienced stress relaxation at the maximum applied stress before failure. Finally, the general fracture behavior of the four new plastics concrete composites under center-point loading was similar to the behavior of the control specimen. Almost all the tested flexural specimens experienced In-Plane shear fracture on the upper surface which was in contact with the applied load while the side surfaces were fractured with a shear angle ranged from about 20^{o} to 30^{o} to the axial load.

From the above findings and since the visual analysis is of a qualitative nature, it can be concluded that research hypothesis 7 may be partially supported while the null hypothesis 7 may be partially rejected.

Conclusions. Based on the visual analysis of the SEM micrographs and the optical photographs generated for the fractured control and plastics concrete composites, the following conclusions can be reported for the research hypothesis 7:

1. The cracking systems in the control concrete composite occurred in two phases: the hcp phase and the tz phase between the aggregate (GR) and hcp. These cracking systems extended in the tz phase and underneath the GR which were pulled out (upon debonding) from the composite. On the other hand, the cracking systems in the cementitious concrete composites containing plastics aggregate substitute occurred in three phases: hcp, tz, and plastics aggregate phases. These cracking systems went through the hcp and propagated through the plastics aggregate causing it to shear.

2. It was noticed that no bonding occurred between the plastic aggregates and the cement paste. This simply means that the plastics aggregate substitute was only used as a filler in all the new concrete composites containing different plastics aggregates percentages.

3. In case of the control concrete composite, some dehydration products in the form of calcium hydroxide (CH) crystals were seen scattered in the empty grooves (resulted from pulling out the GR), voids, and the surface of hcp. On the other hand, the amounts of the CH crystals and plastic particles (scattered in the empty grooves, voids, and the areas of hcp and tz) are more than the amount of CH crystals exited in the control concrete composite. These amounts were increased by the increase of the percentage of plastics aggregate substitute used in concrete composites.

4. Since the new plastics concrete composites had more water and gravel while they were short of sand and plastics, the continuous increase of the water content in these composites, and consequently the water/cement ratio directly affected the porosity in the hcp and tz phases and their strengths. It appeared that the weakness in the hcp and the plastics aggregate phases might have attributed to the reduction of the (f'_c) of the new plastics concrete composites.

5. Increasing the amount of plastic aggregates in concrete composites might have increased the cracking energy required to propagate the initial microcracks to cause fracture of the concrete composite (i.e., the plastics aggregates might have increased the resistance of the composites to cracking).

6. In general, the plastic aggregates worked as crack arrestors and energy absorbers in the new tested plastics concrete composites.

7. By increasing the amount of plastics waste aggregates in concrete cylinders and testing them under uniaxial compression loads, these aggregates were the main reason to hold the shape of these cylinders even after complete failure. This shows that the more the amount of plastics aggregates that was used, the more ductile the fracture of these concrete specimens would be. Slight differences in the fracture behaviors of both the control and 5% plastics concrete cylinders was observed.

8. Identical fracture behaviors were observed for all the plastics concrete composites tested under splitting tensile stress. Furthermore, since the plastics specimens had weaker phases and more initial microcracks than those in the control composite, the crack propagation in the plastics concrete composites was faster than this in the control composite producing more than one main crack (which was observed in the control specimen). These observations may enhance the results obtained from the statistical analysis of the collected data. Unlike the control specimen, the majority of the plastic-containing concrete specimens tested under splitting tensile stress experienced stress relaxation at the maximum applied stress before they failed.

9. Finally, the general fracture behavior of the four new plastics concrete composites under center-point loading (flexure test) was similar to the behavior of the control specimen. Almost all the tested flexural specimens experienced In-Plane shear fracture on the upper surface which was in contact with the applied load while the side surfaces were fractured with a shear angle ranged from about 20° to 30° to the axial load.

Research Hypothesis 8

It is hypothesized that there will be a difference between the microstructure and interfacial bonding of the developed concrete composites using 5, 10, 15, and 20% of glass aggregate substitute added to these composites and those of the control concrete composite.

Glass concrete composites. The visual analysis/findings of the microstructure and general fracture behavior of the control concrete composite were presented above. In case of the glass concrete composites, these new concrete composites had less water and gravel while they had surplus of sand and glass. The continuous reduction of the water content, and consequently the water/cement ratio directly affected the porosity in the tz and hcp phases and their strengths in these composites. In addition, the used glass waste aggregates were finer than the sand aggregates and had predominant angular shapes with sharp edges. This might have caused the new glass concrete composites to have more voids in the tz and hcp phases that can affect the strengths of these phases and composites. SEM micrographs showed that unlike the plastics concrete composites microstructure, there was an interfacial bonding between the used glass aggregates and the cement paste in the glass concrete composites. These glass aggregates acted as crack arrestors and no crack propagation was allowed to propagate through these aggregates. It was also found that the amounts of porosity, CH crystals and crack growth and branching were directly related to the amount of glass aggregates contained in the glass concrete composites. However, in the cases of 5 and 10% glass composites, the glass aggregates were observed to be far apart from each other due to their low amounts while these aggregates were more closer and filled many voids in cases of 15 and 20% glass concrete composites. This may explain the reduction of the ($\underline{f'_c}$) in the former cases and the sudden increase in the later. It was also noticed that the microcracks initiated in the tz phase propagated in the hcp phase in a branching fashion. It was also shown that no cracks propagated underneath the glass aggregates which caused the arrest of other microcracks approaching from surrounding directions. Another observation was the glass aggregate pull-out phenomenon. Comparison of the microstructures of the plastics and glass concrete composites, revealed that the amounts of the CH crystals in the concrete composites at different glass percentages were less than those amounts of CH crystals in the counterpart concrete composites at different plastics percentages. An exception of this observation was in the case of 5% aggregate substitute. Some similarities between the microstructures of the control and 20% glass concrete composites (e.g. cracking systems, interfacial bonding, voids contents, and others) were also identified. This may rationalize why the average ($\underline{f'_c}$) values of these two composites were not significantly different.

It was shown that the majority of the tested concrete cylinders (containing glass aggregate substitute) tested under uniaxial compression load experienced shear or cone and shear type of fracture. A combinations of columnar and shear fracture modes was also experienced by one of the tested cylinders. It was also noticed that the appearance of these concrete cylinders was different from that of control composite. It is to be mentioned that slight differences in the fracture behaviors of both the control and 20% glass concrete cylinders was observed. When a fracture behavior comparison was conducted between the glass and plastics concrete cylinders, the glass concrete cylinders were shattered into small pieces upon failure while most of the plastics concrete cylinders were completely failed and yet held their shapes after failure. This might be attributed to the role played by each of these two waste materials in their concrete composites. In other words, the brittleness of the glass material helped its composites to be more stiffer than those composites containing ductile plastics aggregate specially at higher aggregate percentages. This interpretation, in general, coincides with trend of the flexural modulus of elasticity obtained from the statistical analysis of the collected data.

The behavior of glass concrete composites under splitting tensile loads had some differences from the behavior of the plastics concrete composites under the same type of loads. In case of the glass concrete composites, the initial cracks propagated transversely to the direction of the splitting tensile stress and also branched causing a shear fracture mode to be also present. This cracking system was seen in all the glass concrete composites at different glass aggregate percentages where more area was available to carry the applied splitting tensile loads than that area carried the same type of loads in case of plastics specimens. This made the glass concrete composites able to arrest more cracks than the plastics concrete composites before failure. Yet, the failure of the splitting tensile glass specimens was faster and needed a few bridging cracks (due to the decrease of the frequency of crack arrests) than these cracks found in the compressive glass specimens. This observation was repeated with all the new glass concrete composites (as well as control and plastics concrete composites) under splitting tensile stress. It was also noticed that the fracture behaviors of all the tested glass splitting tensile specimens were almost identical. While the fracture behaviors of 5% and 20% glass specimens were seen to be slightly closer to that behavior of the control specimen, those fracture behaviors of 10% and 15% glass specimens were more closer to the behaviors of their counterparts of plastics specimens. All these observations coincided with the results obtained from the statistical analysis of the collected data. Photographs were obtained to show the general fracture behavior of the four new glass concrete composites under center-point loading (flexure test) disclosed similar behaviors to the control and plastics specimens. Almost all the tested flexural specimens experienced In-Plane shear fracture on the upper surface which was in contact with the applied load. However, the side surfaces were fractured at a shear angle ranged from about 0° to 20° to the axial load. This range of shear angles resembled that of control concrete composite. This meant that both the control and glass concrete composites had some characteristics in common. This observation may support the conclusion drawn through statistical analysis for the collected data which suggested that no significant differences between the (R) value of the control concrete composite and those values of (R) for the glass concrete composites at different aggregate percentages. The maximum shear angle here resembled the minimum shear angle in the case of plastics composites which may indicate that these two different composites had common characteristics at certain aggregate percentages. This observation may be true since it was proven before, from the statistical analysis, that three new concrete composites (containing 5% and 20% glass aggregate as well as 5% plastics aggregate) had higher (R) values than that of control concrete composite. However, it seemed that drawing conclusions or comparing the (R) and (E) values of different concrete composites just based on the visual analysis of the photographs showing the fracture behaviors of these composites should be supported by other scientific methods. For example, generating SEM micrographs for representative samples for these concrete composites may help in relating their general fracture behaviors to their mechanical properties.

From the above findings and since the visual analysis is of a qualitative nature, it can be concluded that research hypothesis 8 may be partially supported while the null hypothesis 8 may be partially rejected.

Conclusions. Based on the visual analysis of the SEM micrographs and optical photographs generated for the fractured control and glass concrete composites, the following conclusions can be reported for the research hypothesis 8:

1. The cracking systems in the control concrete composite occurred in two phases: the hcp phase and the tz phase between the aggregate (GR) and hcp. These cracking systems extended in the tz phase and underneath the GR which were pulled out (upon debonding) from the composite. In the case of glass concrete composites, the microcracks

were initiated in the tz phase and propagated in the hcp phase in a branching fashion. It was also shown that no cracks propagated underneath the glass aggregates which arrested other microcracks approaching from surrounding directions. Another observation was the glass aggregate pull-out phenomenon.

2. It was noticed that there was an interfacial bonding between the used glass aggregates and the cement paste in the glass concrete composites. These glass aggregates acted as crack arrestors and no crack propagation through these aggregates was observed.

3. Since the glass concrete composites had less water and gravel while they had surplus of sand and glass, the continuous reduction of the water content and consequently the water/cement ratio directly affected the porosity in the tz and hcp phases and their strengths in these composites. In addition, the used glass waste aggregates were finer than the sand aggregates and had predominant angular shapes with sharp edges. This might have led for the new glass concrete composites to have more voids in the tz and hcp phases that can affect the strengths of these phases and composites.

4. In the case of the control concrete composite, some dehydration products in the form of calcium hydroxide (CH) crystals were scattered in the empty grooves (resulted from pulling out the GR), voids, and the surface of hcp. On the other hand, the amounts of porosity, CH crystals and crack growth & branching were directly related to the amount of glass aggregates existed in the glass concrete composites.

5. In the cases of 5 and 10% glass composites, the glass aggregates were far apart from each other due to their low amounts while these aggregates were more closer and filled many voids in cases of 15 and 20% glass concrete composites. This may interpret the reduction of the (f'_c) in the former cases and the sudden increase in the later.

6. Some similarities between the microstructures of the control and 20% glass concrete composites (e.g. cracking systems, interfacial bonding, voids contents, and others) were also identified. This may rationalize why the average (f'_c) values of these two composites were not significantly different.

7. The majority of the tested compression glass concrete cylinders experienced shear or cone and shear type of fracture. A combinations of columnar and shear fracture

modes was also experienced by one of the tested cylinders. It was also noticed that the appearance of these concrete cylinders was different from that of control composite except at 20% glass aggregate substitute where slight differences in the fracture behaviors of both the control and 20% glass concrete cylinders was observed.

8. Identical fracture behaviors were observed for all the glass concrete composites tested under splitting tensile stress. The initial cracks in these specimens propagated transversely to the direction of the splitting tensile stress and also branched causing a shear fracture mode to be also present. Yet, failure of all the tested specimens was faster and needed a few bridging cracks than those cracks found in the compressive glass specimens. Meanwhile, the fracture behaviors of 5 and 20% glass specimens were slightly closer to that behavior of the control one. All these observations coincided with the results obtained from the statistical analysis of the collected data.

9. Finally, the general fracture behavior of the four new glass concrete composites under center-point loading (flexure test) was similar to the behavior of the control specimen. Almost all the tested flexural specimens experienced In-Plane shear fracture on the upper surface which was in contact with the applied load while the side surfaces were fractured with a shear angle ranged from about 0° to 30° to the axial load.

10. In general, drawing conclusions or comparing the R and E values of different concrete composites just based on the visual analysis of the photographs showing the fracture behaviors of these composites seemed to be not scientifically sound. Generating SEM micrographs for representative samples for these concrete composites may help in relating their general fracture behaviors to their mechanical properties.

Research Hypothesis 9

It is hypothesized that there will be a difference between the microstructure and interfacial bonding of the new concrete composites using 5, 10, 15, and 20% of fiberglass aggregate substitute added to these composites and those of the control concrete composite.

Fiberglass concrete composites. The visual analysis/findings of the microstructure and general fracture behavior of the control concrete composite were presented earlier. On the other hand, it was found that the rate of reduction in the overall (FM) in the case of fiberglass concrete composites was higher than that of glass ones. These new fiberglass concrete composites had the least amounts of water and gravel while they had the highest amounts of fine aggregates (fiberglass and sand) among the three types of new concrete composites used. The continuous reduction of the water content and consequently the water/cement ratio directly affected the porosity in the tz and hcp phases and their strengths.

SEM micrographs showed that the glass fiber filaments were randomly distributed in the concrete matrix and their surface remained as smooth as before curing. These glass fibers acted as crack arrestors. It appears that the growth of hydration products on the glass fibers filaments provided excessive bonding between fibers and matrix which eliminated fiber pull-out prior to fracture. This was clearly observed especially when the amount of glass fibers was maximum among the four tested concrete composites. It was also noticed that the unsaturated polyester base resin (styrene) had no bonding with the concrete matrix in their transition zone which made this zone weak. Also the amounts of the hydration products and styrene particles were increased extremely in these concrete composites with the increase of the fiberglass aggregate percentages. Since the amount of polymers in the fiberglass waste material was higher than that of glass fiber filaments, the strength of the concrete composites depended basically on the tz phase between the concrete matrix and the glass fibers filaments. On the contrary, the hcp and tz (between styrene and concrete matrix) phases were the main sources for failure in these concrete composites. With the increase of the fiberglass aggregate percentage in the concrete composites, the area responsible for strengthening the concrete composites was reduced while the weakening area in these concrete composites was increased. This weakening area might have attributed to the continuous reduction of the compressive strength of the new fiberglass concrete composites. This conclusion was supported by the generated SEM micrographs which showed that the microcracking area increased with the increase of percentages of fiberglass aggregate.

SEM micrographs suggested that no significant differences should be expected among all the new composites containing up to 10% aggregate substitute materials since the existence of these materials in the concrete composites was scarce. This observation is generally supported by both the statistical and graphical analyses presented before. However, basic and important features of each concrete composite were clearly shown: the propagation of the crack through the plastics aggregates which were not bonded with the cement paste; the good interfacial bonding between the cement paste and glass aggregates which acted as crack arrestors preventing crack from propagating through them; the strong bonding between the glass fiber filaments (crack arrestors) and cement paste which was not bonded with the unsaturated polyester base resin (styrene). On the other hand, when higher percentages of aggregate substitutes were added, significant differences were seen among the new concrete composites (e.g. aggregates density and distribution, porosity, hydration products, pull out phenomenon, cracking patterns).

Photographs generated for the general fracture behaviors of all the new fiberglass concrete composites tested under uniaxial compression loads showed that the fracture behavior of the 5 and 20% fiberglass specimens was of cone and shear mode while the 10 and 15% fiberglass specimens experienced pure shear fracture and a combination of columnar and shear fracture modes respectively. It was also noticed that the shape of the fractured fiberglass cylinders was different from those of the fractured plastics cylinders. In other words, no microcracks were detected on the outer surfaces of the fiberglass cylinders as those that appeared on the plastics ones (especially those cylinders at 15 and 20% aggregate substitute). This observation may also suggest that the general fracture behavior of the fiberglass specimens is not driven by the glass fiber filament but rather by the powder unsaturated polyester base resin. In other words, if the plastics fine aggregates are very coarse (their FM is larger than that of sand aggregates), the fracture behavior of these composites will tend to be of a ductile mode. On the other hand, these composites will show brittle fracture mode if they contain very fine plastics aggregates. It was also noticed that the appearance of the fiberglass concrete cylinders (which was basically very close to that of glass composites) was relatively different from that of control composite.

Photographs of the general behavior of the fiberglass concrete composites under splitting tensile loads showed that these fractured specimens combined some features that were characteristic of these shown in the plastics and glass concrete composites tested under the same type of loads. The first feature observed was that the failure of the fiberglass specimens was faster and needed a few bridging cracks than those cracks found in the compressive fiberglass specimens. This was observed repeatedly with all the tested plastics and glass concrete composites under the same type of loads. The second observed feature was that almost all the fractured fiberglass specimens were easy to handle after testing without damaging their original shape. In other words, the tested fiberglass specimens held their integrity even after testing resembling the behavior of the plastics concrete composites under the same type of loads. This feature was not experienced with the glass concrete specimens. In fact, extra precautions was needed to maintain and preserve the shapes of the fractured glass concrete composites in order to generate the photographs shown before. The third feature observed was the fracture modes of each fiberglass concrete composite tested under splitting tensile loads. For example, the initial cracks in the 5 and 10% fiberglass concrete composites propagated only transversely to the direction of the splitting tensile stress resembling the behavior of the plastics concrete composites. On the other hand, the initial cracks in the 15 and 20% fiberglass concrete composites propagated transversely to the direction of the splitting tensile stress and also branched causing a shear fracture mode to be also present. This cracking system was also experienced by the glass concrete composites. This enabled the 15% and 20% fiberglass (as well as all the glass) concrete composites to arrest more cracks than the plastics concrete composites before failure. However, the collected data showed that the (T) values for the 15 and 20% fiberglass concrete composites were slightly lower than those for 5 and 10% fiberglass concrete composites. This observation and conclusion contradicts the conclusion drawn from the visual analysis conducted to compare the behaviors of the glass and plastics concrete composites and relate their general fracture behaviors to their (T) values. This contradiction simply suggests that relating the general fracture behavior of the concrete composites to their mechanical properties should only be based on qualitative base.

As a conclusion of the visual analysis of the general fracture behavior of the tested splitting tensile specimens, there were similarities and slight differences among all the three different types of concrete composites (plastics, fiberglass, and glass). In more details, the general fracture behavior of all the tested plastics concrete specimens at different percentages of aggregate substitute was basically the same. Same conclusion was also drawn for the fracture behavior of all the glass concrete specimens. In case of fiberglass concrete specimens, the fracture behavior of these specimens was a combination between the behavior of plastics and glass concrete specimens. In addition, the majority of the splitting tensile concrete composites fractured in a different fashion than that of the control specimen. These conclusions match those arrived at from the statistical and graphical analyses to a great extent. Based on the present research, it is believed that the visual analysis technique should be strongly recommended to compare the properties of different types of concrete composites qualitatively. This technique may be also used to predict whether different concrete composites have the same brittle or ductile fracture modes under splitting tensile loads.

Photographs of the general fracture behavior of the four new fiberglass concrete composites under center-point loading (flexure test) showed that the general behavior of these tested fiberglass flexural specimens was basically the same as those behaviors of the control, plastics, and glass specimens. Almost all the tested flexural specimens experienced In-Plane shear fracture on the upper surface which was in contact with the applied load. However, the side surfaces were fractured at a shear angle ranged from about 5^o to 35^o to the axial load. This range of shear angles may approach the lower and upper limits for the other concrete composites (0^o-20^o for glass and control concrete specimens and 20^o-30^o for the plastics specimens). This meant that there were common characteristics among all the control and new concrete composites. This observation may support some of the conclusions drawn through statistical and graphical analyses for the collected data which suggest that no significant differences among the (R) and (E) values of the control and new concrete composites at certain aggregate percentages (such as 5%). However, it is difficult to draw general conclusions or to compare the R and E values of different concrete composites based just on the visual analysis of the photographs showing the fracture behaviors of these composites. Once more, generating SEM micrographs for representative samples for these concrete composites may help in relating their general fracture behaviors and their mechanical properties.

From the above findings and since the visual analysis is of a qualitative nature, it can be concluded that research hypothesis 9 may be partially supported while the null hypothesis 9 may be partially rejected.

Conclusions. Based on the visual analysis for the SEM micrographs and photographs generated for the fractured control and glass concrete composites, the following conclusions can be reported for the research hypothesis 9:

1. The cracking systems in the control concrete composite occurred in two phases: the hydrated cement paste (hcp) phase and the interfacial region (transition zone. tz) between the aggregate (GR) and hcp. These cracking systems extended in the tz phase and underneath the GR which were pulled out (upon debonding) from the composite. In case of fiberglass concrete composites, the hcp and tz (between styrene and concrete matrix) phases were the main sources for failure in these concrete composites. By increasing the percentages of fiberglass aggregate used in concrete composites, the microcracking area was also increased. These microcracks were initiated in the tz phase and propagated in the hcp phase in a branching fashion.

2. It was noticed that the glass fiber filaments acted as crack arrestors due to the growth of hydration products within the glass fibers filaments which provided excessive bonding between the fibers and matrix which eliminated fiber pull-out prior to fracture.

3. In the case of the control concrete composite. some dehydration products in the form of calcium hydroxide (CH) crystals were scattered in the empty grooves (resulted from pulling out the GR). voids. and the surface of hcp. On the other hand, in the case of fiberglass concrete composites, it was noticed that the unsaturated polyester base resin (styrene) had no bonding with the concrete matrix in their transition zone which was weak. Also the amounts of the hydration products and styrene particles were extremely increased in these concrete composites with the increase of the fiberglass aggregate percentages. Since the amount of polymers in the fiberglass waste material was higher than that of glass

fiber filaments, the strength of the concrete composites depended basically on the tz phase between the concrete matrix and the glass fibers filaments.

4. Since the fiberglass concrete composites had the least amount of water and gravel while they had surplus of sand and fiberglass, the continuous reduction of the water content and consequently the water/cement ratio directly affected the porosity in the tz and hcp phases and their strengths in these composites. In addition, the used fiberglass waste aggregates were the finest aggregates used in the present study. This might have led to the new fiberglass concrete composites to have more voids in the tz and hcp phases that can affect the strengths of these phases and composites.

5. Under uniaxial compression loads, the fracture behavior of the 5 and 20% fiberglass concrete composites was of cone and shear mode while the 10 and 15% fiberglass concrete composites experienced pure shear fracture and a combination of columnar and shear fracture modes respectively. It was also noticed that the appearance of the fiberglass concrete cylinders was different from that of the control composite.

6. The general fracture behavior of the fiberglass concrete composites was not driven by the glass fiber filament but by the powder unsaturated polyester base resin. In other words, if the plastics fine aggregates are very coarse (their FM is larger than that of sand aggregates), the fracture behavior of the new concrete composites would tend to be of a ductile mode. On the other hand, these new concrete composites would show brittle fracture mode if they contain very fine plastics aggregates.

7. Under splitting tensile stresses, the failure of the fiberglass specimens was faster and needed a few bridging cracks than those cracks found in the compressive fiberglass specimens. This fracture mode was different from that of the control specimen.

8. Finally, the general fracture behavior of the four new fiberglass concrete composites under center-point loading (flexure test) was similar to the behavior of the control specimen. Almost all the tested flexural specimens experienced In-Plane shear fracture on the upper surface which was in contact with the applied load while the side surfaces were fractured with a shear angle ranged from about 5° to 35° to the axial load.

This range of shear angles may approach the lower and upper limits for the other concrete composites (0^{o}-20^{o} for glass and control concrete specimens and 20^{o}-30^{o} for the plastics specimens). This meant that there was common characteristics among all the control and new concrete composites. This observation may support some of the conclusions drawn through statistical and graphical analyses for the collected data which suggest that no significant differences among the (R) and (E) values of the control and new concrete composites at certain aggregate percentages (such as 5%).

9. Based on the present research, it is believed that the visual analysis technique is strongly recommended to compare the properties of different types of concrete composites qualitatively. This technique may also be used to predict whether different concrete composites have the same brittle or ductile fracture modes under splitting tensile loads.

Research Hypothesis 10

It is hypothesized that there will be observable differences between the microstructure and interfacial bonding of the developed concrete composites using 5, 10, 15, and 20% of plastics aggregate substitute added to these composites and those microstructure and interfacial bonding of the new concrete composites using the same percentages of glass aggregate substitute.

Plastics and glass concrete composites. The visual analysis/findings of the microstructure and general fracture behavior of the plastics and glass concrete composite were presented earlier. From these findings and since the visual analysis is of a qualitative nature, it can be concluded that research and null hypotheses 10 may be partially supported and rejected respectively.

Conclusions. Based on the visual analysis of the SEM micrographs and photographs generated for the fractured control and glass concrete composites, the following conclusions can be reported for the research hypothesis 10:

1. The cracking systems in the plastics-containing concrete composites occurred in three phases: hcp, tz, and plastics aggregate phases. These cracking systems went through the hcp and propagated through the plastics aggregate causing it to shear. In case of the

glass-containing concrete composites, the microcracks were initiated in the tz phase and propagated in the hcp phase in a branching fashion.

2. It was noticed that no bonding occurred between the plastic aggregates and the cement paste. This simply means that the plastics aggregate substitute was only used as a filler in all the new concrete composites containing different percentages of plastics-containing aggregates. They also acted as crack arrestors and energy absorbers in the new tested plastics concrete composites. On the other hand, there was an interfacial bonding between the used glass aggregates and the cement paste in the glass concrete composites. These glass aggregates worked as crack arrestors and no crack propagation was observed through these aggregates.

3. Comparison of the microstructures of the plastics and glass concrete composites showed that the amounts of the CH crystals in the concrete composites at different glass percentages were less than those amounts of CH crystals which exited in the counterpart concrete composites at different plastics percentages. An exception for this observation was in the case of 5% aggregate substitute.

4. Since the new plastics concrete composites had more water and gravel while they were short of sand and plastics, the continuous increase of the water content in these composites and consequently the water/cement ratio directly affected the porosity in the hcp and tz phases and their strengths. It appeared that the weakness in the hcp and the plastics aggregate phases might have contributed to the reduction of the (f'_c) of the new plastics concrete composites. On the other hand, since the glass concrete composites had less water and gravel while they had surplus of sand and glass, the continuous reduction of the water content and consequently the water/cement ratio directly affected the porosity in the tz and hcp phases and their strengths in these composites. In addition, the used glass waste aggregates were finer than the sand aggregates and had predominant angular shapes with sharp edges. This might have led to the new glass concrete composites to have more voids in the tz and hcp phases that can affect the strengths of these phases and composites. It appears that the amount of the used glass aggregates and their distribution were among the driving factors affecting the (f'_c) values of the glass concrete composites.

5. Increasing in the amount of the substituted plastic aggregates in concrete composites is believed to have increased the cracking energy required to propagate the initial microcracks to cause fracture of the concrete composite (i.e., the plastics aggregates might have increased the resistance of the composites to cracking).

6. It was shown that the majority of the tested glass-contained concrete cylinders experienced shear or cone and shear type of fracture. A combinations of columnar and shear fracture modes was also experienced by one of the tested cylinders. Ductile fracture mode was experienced by the majority of the plastics concrete composites.

7. When a fracture behavior comparison was conducted between the glass and plastics concrete cylinders, the glass concrete cylinders were shattered into small pieces upon failure while most of the plastics concrete cylinders were completely failed and yet held their shapes after failure. This might be attributed to the role played by each of these two waste materials in their concrete composites. In other words, the brittleness of the glass material helped its composites to be more stiffer than those composites containing ductile plastics aggregate specially at higher aggregate percentages. This interpretation, in general, coincides with trend of the flexural modulus of elasticity obtained from the statistical analysis of the collected data.

8. The behavior of glass concrete composites under splitting tensile loads had some differences from the behavior of the plastics concrete composites under the same type of load where the initial cracks propagated transversely to the direction of the splitting tensile stress and also branched causing a shear fracture mode to be also present. This cracking system was seen in all the glass concrete composites at different glass aggregate percentages where more area was available to carry the applied splitting tensile loads than that area carried the same type of loads in case of plastics specimens. This enabled the glass concrete composites to arrest more cracks than the plastics concrete composites before failure. However, the fracture behaviors of 10% and 15% glass specimens were more closer to the behaviors of their counterparts of plastics-containing specimens. All these observations coincided with the results obtained from the statistical analysis of the collected data. Finally, unlike the glass specimens, the majority of the plastics concrete specimens

tested under splitting tensile stress experienced stress relaxation at the maximum applied stress before they failed.

9. Finally, the general fracture behavior of the four new glass concrete composites under center-point loading (flexure test) was almost similar to the behavior of the plastics specimen. In other words, the maximum shear angle in this case resembled the minimum shear angle in case of plastics composites which may indicate that these two different composites had common characteristics at certain aggregate percentages. This observation may be true since it was proven before, from the statistical analysis, that three new concrete composites (containing 5% and 20% glass aggregate as well as 5% plastics aggregate) had higher R values than that of control concrete composite.

10. In general, drawing conclusions or comparing the (R) and (E) values of different concrete composites based just on the visual analysis of the photographs showing the fracture behaviors of these composites seemed to be qualitatively sound. Generating SEM micrographs for representative samples for these concrete composites may also help in relating their general fracture behaviors to their mechanical properties.

Research Hypothesis 11

It is hypothesized that there will be observable differences between the microstructure and interfacial bonding of the developed concrete composites using 5, 10, 15, and 20% of plastics aggregate substitute added to these composites and those microstructure and interfacial bonding of the new concrete composites using the same percentages of fiberglass aggregate substitute.

Plastics and fiberglass concrete composites. The visual analysis/findings of the microstructure and general fracture behavior of the plastics and fiberglass concrete composite were presented earlier. From these findings and since the visual analysis is of a qualitative nature, it can be concluded that research and null hypotheses 11 may be partially supported and rejected respectively.

Conclusions. Based on the visual analysis of the SEM micrographs and photographs generated for the fractured control and glass concrete composites, the following conclusions can be reported for the research hypothesis 11:

1. The cracking systems in cementitious concrete composites containing plastics aggregate substitute occurred in three phases: hcp, tz, and plastics aggregate phases. These cracking systems went through the hcp and propagated through the plastics aggregate causing it to shear. In case of fiberglass concrete composites, the hcp and tz (between styrene and concrete matrix) phases were the main sources for failure in these concrete composites. By increasing the percentages of fiberglass aggregate used in concrete composites, the microcracking area was also increased. These microcracks were initiated in the tz phase and propagated in the hcp phase in a branching fashion.

2. It was noticed that no bonding occurred between the plastic aggregates and the cement paste. This simply means that the plastics aggregate substitute was only used as a filler in all the new concrete composites containing different percentages of plastics aggregates. They also acted as crack arrestors and energy absorbers in the tested plastics concrete composites. On the other hand, it was noticed that the glass fiber filaments acted as crack arrestors due to the growth of hydration products within the glass fibers filaments which provided excessive bonding between the fibers and matrix which eliminated fiber pull-out prior to fracture. On the contrary, the unsaturated polyester base resin (styrene) had no bonding with the concrete matrix in their transition zone which was weak.

3. Comparison of the microstructures of the plastics and fiberglass concrete composites, it was seen that the amounts of the CH crystals and plastics aggregates increased in the plastics composites with the increase of plastics percentages. On the other hand, the amounts of the hydration products and styrene particles were extremely increased in the fiberglass composites with the increase of the fiberglass aggregate percentages.

4. Since the new plastics concrete composites had more water and gravel while they were short of sand and plastics, the continuous increase of the water content in these composites and consequently the water/cement ratio directly affected the porosity in the hcp and tz phases and their strengths. It appeared that the weakness in the hcp and the plastics aggregate phases might have attributed to the reduction of the ($\underline{f'_c}$) of the new plastics concrete composites. On the other hand, since the fiberglass concrete composites had the least amount of water and gravel while they had surplus of sand and fiberglass, the

continuous reduction of the water content and consequently the water/cement ratio directly affected the porosity in the tz and hcp phases and their strengths in these composites. In addition, the used fiberglass waste aggregates were the finest aggregates used in the present study. This might have led for the new fiberglass concrete composites to have more voids in the tz and hcp phases that can affect the strengths of these phases and composites.

5. SEM micrographs suggested that no significant differences should be expected among all the new composites containing up to 10% aggregate substitute materials since the existence of these materials in the concrete composites was scarce. However, some basic and important features of plastics and fiberglass concrete composites were clearly shown: the propagation of the crack through the plastics aggregates which were not bonded to the cement paste and the strong bonding between the glass fiber filaments (crack arrestors) and cement paste which was not bonded with the unsaturated polyester base resin (styrene). On the other hand, when higher percentages of aggregate substitutes were added, significant differences were seen between these composites (e.g. aggregates density and distribution, porosity, hydration products, pull out phenomenon, cracking patterns).

6. Under uniaxial compression loads, the fracture behavior of the 5 and 20% fiberglass concrete composites was of cone and shear mode while the 10 and 15% fiberglass concrete composites experienced pure shear fracture and a combination of columnar and shear fracture modes respectively. It was also noticed that the appearance of the fiberglass concrete cylinders was different from those of plastics composites. Ductile fracture mode was experienced by the majority of the plastics concrete composites.

7. The shape of the fractured fiberglass cylinders was different from those of the fractured plastics cylinders since no microcracks were detected on the outer surfaces of the fiberglass cylinders as those appeared on the plastics cylinders (especially those cylinders at 15 and 20% aggregate substitute). This observation may also suggest that the general fracture behavior of the fiberglass concrete composites was driven by the powder unsaturated polyester base resin. In general, very coarse plastics fine aggregates with FM larger than that of sand aggregates may lead the fracture behavior of the new concrete

composites to be of a ductile mode. On the other hand, these new concrete composites will show brittle fracture mode if they contain very fine plastics aggregates.

8. The behavior of fiberglass concrete composites under splitting tensile loads had some similarities and differences from the behavior of the plastics concrete composites under the same type of loads. The first similarity was that the failure of the fiberglass specimens was faster and needed a few bridging cracks than those cracks found in the compressive fiberglass specimens (this observation was repeated with all the tested plastics and glass concrete composites). The second similarity observed was that almost all the fractured fiberglass specimens were easy to handle after testing without damaging their original shape (i.e. the tested fiberglass specimens held their integrity even after testing resembling the behavior of the plastics concrete composites). On the other hand, while the initial cracks in the 5 and 10% fiberglass concrete composites propagated only transversely to the direction of the splitting tensile stress resembling the behavior of the plastics concrete composites, the initial cracks in the 15 and 20% fiberglass concrete composites propagated transversely to the direction of the splitting tensile stress and also branched causing a shear fracture mode to be also present. This made the 15% and 20% fiberglass concrete composites able to arrest more cracks than the plastics concrete composites before failure.

9. Finally, the general fracture behavior of the four fiberglass concrete composites under center-point loading was similar, to some extent, to the behavior of the plastics ones. Almost all the tested flexural beams experienced In-Plane shear fracture on the upper surface which was in contact with the applied load while the side surfaces were fractured with a shear angle ranged from about 5^{o} to 35^{o} to the axial load. This range of shear angles may approach the lower and upper limits for the plastics composites (20^{o}-30^{o}). This observation may support some of the conclusions drawn through statistical and graphical analyses which suggest that no significant differences among the (R) and (E) values of the plastics and fiberglass concrete composites at certain aggregate percentages (such as 10%).

10. Based on the present research study, it is believed that the visual analysis technique should be strongly recommended to compare the properties of different types of

concrete composites qualitatively. This technique may be also used to predict whether different concrete composites have the same brittle or ductile fracture modes under splitting tensile loads.

Research Hypothesis 12

It is hypothesized that there will be observable differences between the microstructure and interfacial bonding of the developed concrete composites using 5, 10, 15, and 20% of glass aggregate substitute added to these composites and those features of the new concrete composites using the same percentages of fiberglass aggregate substitute.

Glass and fiberglass concrete composites. The visual analysis/findings of the microstructure and general fracture behavior of the glass and fiberglass concrete composites were presented earlier. From these findings and since the visual analysis is of a qualitative nature, it can be concluded that research and null hypotheses 12 may partially be supported and rejected respectively.

Conclusions. Based on the visual analysis of the SEM micrographs and photographs generated for the fractured control and glass concrete composites, the following conclusions can be drawn for the research hypothesis 12:

1. In case of fiberglass concrete composites, the hcp and tz (between styrene and concrete matrix) phases were the main sources for failure in these concrete composites. By increasing the percentages of fiberglass aggregate used in concrete composites, the microcracking area was also increased. These microcracks were initiated in the tz phase and propagated in the hcp phase in a branching fashion. On the other hand, the microcracks were initiated in the tz phase and propagated in the hcp phase in a branching fashion in the glass concrete composites.

2. It was noticed that there was an interfacial bonding between the used glass aggregates and the cement paste in the glass concrete composites. These glass aggregates acted as crack arrestors and no crack propagation was seen through these aggregates. On the other hand, the glass fiber filaments acted as crack arrestors due to the growth of hydration products within the glass fibers filaments which provided excessive bonding between the fibers and matrix which eliminated fiber pull-out prior to fracture. On the

contrary, the unsaturated polyester base resin (styrene) had no bonding with the concrete matrix in their transition zone which was weak.

3. Comparison of the microstructures of the fiberglass and glass concrete composites, it was seen that the amounts of the CH crystals in the concrete composites at different glass percentages were less than those amounts of the hydration products and styrene particles which were extremely increased in the fiberglass concrete composites with the increase of the fiberglass aggregate percentages. An exception for this observation was in the case of 5% aggregate substitute.

4. It was found that the rate of reduction in the overall (FM) in the case of fiberglass concrete composites was higher than that of the glass ones. These new fiberglass concrete composites had the least amounts of water and gravel while they had the highest amounts of fine aggregates (fiberglass and sand) among the three types of new concrete composites used. The continuous reduction of the water content and consequently the water/cement ratio directly affected the porosity in the tz and hcp phases and their strengths. On the other hand, the used glass waste aggregates had predominant angular shapes with sharp edges. This might have led to the new glass concrete composites to have more voids in the tz and hcp phases that can affect the strengths of these phases and composites. It appears that the amount of the used glass aggregates and their distribution were among the driving factors affecting the (f'_c) values of the glass concrete composites.

5. SEM micrographs suggested that no significant differences should be expected among all the new composites containing up to 10% aggregate substitute materials since the existence of these materials in the concrete composites was scarce. However, basic and important features of glass and fiberglass concrete composites were clearly shown: the good interfacial bonding between the cement paste and glass aggregates which worked as crack arrestors preventing crack from propagating through them and the strong bonding between the glass fiber filaments (crack arrestors) and cement paste which was not bonded with the unsaturated polyester base resin (styrene). On the other hand, when higher percentages of aggregate substitutes were added, significant differences were seen between

these new concrete composites (e.g. aggregates density and distribution, porosity, hydration products, pull out phenomenon, cracking patterns).

6. Under uniaxial compression loads, the fracture behavior of the 5 and 20% fiberglass concrete composites was of cone and shear mode while the 10 and 15% fiberglass concrete composites experienced pure shear fracture and a combination of columnar and shear fracture modes respectively. On the other hand, the majority of the tested glass concrete cylinders experienced shear or cone & shear type of fracture. A combinations of columnar & shear fracture modes was also experienced by one of the tested glass cylinders. It was also noticed that the appearance of the fiberglass concrete cylinders was basically very close to that of glass composites.

7. The behavior of fiberglass concrete composites under splitting tensile loads had some similarities and differences from the behavior of the glass concrete composites under the same type of loads. The first feature was that the failure of the fiberglass specimens was faster and needed a few bridging cracks than those cracks found in the compressive fiberglass specimens (this observation was repeated with all the tested plastics and glass concrete composites). The second feature observed in the fiberglass concrete composites was that almost all the fractured fiberglass specimens were easy to handle after testing without damaging their original shape. In other words, the tested fiberglass specimens held their integrity even after testing where the glass concrete specimens needed extra care to maintain and preserve the shapes of the fractured glass composites in order to generate the photographs shown before. The third feature was the fracture modes of each fiberglass concrete composite tested under splitting tensile loads where the initial cracks in the 5 and 10% fiberglass concrete composites propagated only transversely to the direction of the splitting tensile stress resembling the behavior of the plastics concrete composites. On the other hand, the initial cracks in the 15 and 20% fiberglass concrete composites propagated transversely to the direction of the splitting tensile stress and also branched causing a shear fracture mode to be also present. This cracking system which was also experienced by the glass concrete composites made the 15 and 20% fiberglass (as well as all the glass) composites able to arrest more cracks than the plastics concrete composites before failure.

8. Finally, the general fracture behavior of the four new fiberglass concrete composites under center-point loading (flexure test) was similar, to some extent, to the behavior of the glass specimens. Almost all the tested flexural specimens experienced In-Plane shear fracture on the upper surface which was in contact with the applied load while the side surfaces were fractured with a shear angle ranged from about 5° to 35° to the axial load. This range of shear angles may approach the lower and upper limits for the glass concrete composites (0°-20°). This observation may support some of the conclusions drawn through statistical and graphical analyses for the collected data which suggest that no significant differences among the R and E values of the glass and fiberglass concrete composites at certain aggregate percentages (such as 5%).

Recommendations

The following recommendations are made in view of the findings of this study:

1. The present investigation has been conducted on only three solid waste materials, out of all the materials that exist in the solid waste stream. Similar studies should be conducted on other solid waste materials such as commingled waste plastics, waste rubber, waste metals, and others.

2. This investigation considered only solid waste materials as fine aggregate substitutes up to 20% of the volume of sand aggregates. It would be of interest to study the effect of increasing these percentages especially in the cases of glass and plastics waste materials.

3. The three different solid waste materials considered in the current study had fineness modulus (FM) values different from that of sand aggregates. It is recommended to study the effect of these materials (and others) on the properties of the cementitious concrete composite fixing the FM values for all these fine aggregates.

4. The present study considered only SEM micrographs of fractured compression specimens to establish structure-properties relationships for the different types of cementitious concrete composites. It is recommended to produce SEM micrographs of all the fractured specimens tested under different loading conditions and increase the number

of tested specimens under SEM to obtain better representation for each composite and consequently to establish strong structure-properties relationships for all the tested composites.

5. The plastics waste aggregate materials used in the current research were not bonded to the cement paste in the cementitious concrete composites. It is recommended to study the feasibility of using chemically treated plastic aggregates and their effects on the properties of the cementitious concrete composite.

6. The present study considered only testing the developed cementitious concrete composites at ambient temperature. It is recommended to test these composites and others under different temperatures (elevated as well as subzero temperatures) to characterize the actual behavior of these composites under real life working conditions.

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Appendix A

The Maximum Applied Loads and Corresponding (f'_c) for The New Cementitious Concrete Composites Containing Plastics, Glass, and Fiberglass at Different Volume Percentages

Number of tested samples at each percentage of aggregate substitute		Type of fine aggregate substitute in new cementitious concrete composite and the maximum applied load and compressive strength (f'_c) for this composite					
		Plastics		Glass		Fiberglass	
		Load (lb)	f'_c (psi)	Load (lb)	f'_c (psi)	Load (lb)	f'_c (psi)
	1	31130	4400	31710	4490	30640	4340
	2	34120	4830	29780	4210	30840	4360
5%	3	31620	4470	32090	4540	32380	4580
	4	30640	4340	35480	5020	33740	4770
	5	29190	4040	22910	3240	29770	4210
Average Value		31340	4420	30390	4300	31470	4450
Standard Deviation		1800	250	4660	600	1580	220
	1	28810	4080	32100	4540	27940	3950
	2	28900	4090	32380	4580	29390	4160
10%	3	25230	3570	27550	3900	29100	4120
	4	26780	3790	27360	3870	26100	3690
	5	26780	3790	24940	3530	29390	4160
Average Value		27300	3860	28870	4080	28380	4020
Standard Deviation		1550	220	3250	460	1410	200
	1	25620	3620	26600	3670	25040	3540
	2	25810	3650	30450	4310	30060	4250
15%	3	22240	3150	32770	4640	28230	3990
	4	18950	2680	25130	3560	25040	3540
	5	23490	3320	28610	4050	25910	3670
Average Value		23220	3280	28570	4050	25860	3800
Standard Deviation		2820	400	3170	400	2220	310
	1	27740	3930	37410	5290	27940	3950
	2	28610	4050	35900	4940	26490	3750
20%	3	29970	4240	35770	5060	17590	2490
	4	29580	4180	34320	4860	20400	2890
	5	28610	4050	35670	5050	20780	2940
Average Value		28900	4090	35610	5040	22640	3200
Standard Deviation		880	120	1170	160	4380	620

Appendix B

The Maximum Applied Loads and Corresponding (T) for The New Cementitious Concrete Composites Containing Plastics, Glass, and Fiberglass at Different Volume Percentages

Number of tested samples at each percentage of aggregate substitute	Type of fine aggregate substitute in new cementitious concrete composite and the maximum applied load and splitting tensile strength (T) for this composite					
	Plastics		Glass		Fiberglass	
	Load (lb)	T (psi)	Load (lb)	T (psi)	Load (lb)	T (psi)
1	14695	540	16725	605	16630	610
2	9860	365	13920	505	13920	495
5% 3	10730	395	15180	550	12375	440
4	12280	450	11795	420	13920	500
5	12470	455	13050	470	12470	450
6	11700	420	11410	420	12470	475
Average Value	11955	440	13680	495	13630	495
Standard Deviation	1665	60	2035	75	1640	60
1	10540	375	13825	510	14210	505
2	11310	415	12570	460	13150	475
10% 3	13730	505	13245	485	12280	450
4	10925	400	13535	495	16050	560
5	12375	450	13150	475	13150	475
6	11600	420	12470	460	15080	545
Average Value	11745	430	13135	480	13985	500
Standard Deviation	1155	45	530	20	1400	45
1	13150	480	13630	490	14695	520
2	12280	440	9860	360	13535	485
15% 3	13730	495	12570	455	12470	440
4	9765	355	10830	390	12375	450
5	12760	465	12760	465	14500	505
6	12470	450	12280	445	12280	470
Average Value	12360	450	11990	435	13310	480
Standard Deviation	1370	50	1385	50	1100	30
1	9180	330	13630	495	13340	475
2	11700	425	12860	470	12955	460
20% 3	12375	455	12470	455	13920	490
4	12955	465	14115	510	14890	520
5	13150	470	14110	515	12470	450
6	13440	480	13245	475	10925	415
Average Value	12135	440	13405	485	13085	470
Standard Deviation	1575	60	670	25	1350	35

Appendix C

The Maximum Applied Loads and Corresponding (R) for The New Cementitious Concrete Composites Containing Plastics, Glass, and Fiberglass at Different Volume Percentages

Number of tested samples at each percentage of aggregate substitute	Type of fine aggregate substitute in new cementitious concrete composite and the maximum applied load and modulus of rupture (R) for this composite					
	Plastics		Glass		Fiberglass	
	Load (lb)	R (psi)	Load (lb)	R (psi)	Load (lb)	R (psi)
1	850	955	705	800	705	760
2	720	820	750	870	795	865
5% 3	855	935	900	1020	725	790
4	915	1055	865	1010	835	810
5	835	955	750	845	825	870
Average Value	835	945	795	910	755	820
Standard Deviation	70	85	85	100	50	50
1	695	800	950	920	755	840
2	770	860	915	955	715	770
10% 3	720	800	800	850	785	850
4	665	755	745	810	780	835
5	700	790	780	835	695	730
Average Value	710	800	840	875	745	805
Standard Deviation	40	40	90	60	40	50
1	650	655	720	780	715	795
2	610	660	800	880	700	730
15% 3	590	640	760	850	655	705
4	550	600	680	765	685	705
5	630	695	765	835	720	785
Average Value	605	650	745	820	695	745
Standard Deviation	40	35	45	50	25	45
1	610	640	830	860	725	760
2	605	665	865	875	730	765
20% 3	660	715	840	870	740	775
4	580	640	1005	1015	695	730
5	470	515	900	940	775	780
Average Value	585	635	890	910	735	760
Standard Deviation	70	75	70	65	30	20

Appendix D

The Maximum Applied Loads and Corresponding (E) for The New Cementitious Concrete Composites Containing Plastics, Glass, and Fiberglass at Different Volume Percentages

Number of tested samples at each percentage of aggregate substitute	Type of fine aggregate substitute in new cementitious concrete composite and the maximum applied load and modulus of elasticity (E) for this composite					
	Plastics		Glass		Fiberglass	
	Load (lb)	E (Ksi)	Load (lb)	E (Ksi)	Load (lb)	E (Ksi)
1	850	105.91	705	88.03	705	70.85
2	720	50.87	750	55.08	795	102.02
5% 3	855	109.17	900	83.40	725	70.69
4	915	126.66	865	55.40	835	84.76
5	835	104.38	750	76.33	825	79.69
Average Value	835	99.40	795	71.65	755	81.60
Standard Deviation	70	28.55	85	15.55	50	12.90
1	695	59.00	950	55.76	755	108.41
2	770	74.53	915	69.74	715	66.33
10% 3	720	53.77	800	63.12	785	109.03
4	665	84.25	745	58.00	780	90.49
5	700	81.68	780	66.10	695	80.37
Average Value	710	70.65	840	62.54	745	90.93
Standard Deviation	40	13.62	90	05.73	40	18.37
1	650	57.18	720	88.36	715	120.81
2	610	61.05	800	89.00	700	80.70
15% 3	590	68.72	760	85.19	655	72.59
4	550	68.38	680	60.53	685	58.78
5	630	56.44	765	87.88	720	118.43
Average Value	605	62.35	745	82.19	695	90.86
Standard Deviation	40	05.92	45	12.20	25	27.49
1	610	61.31	830	83.68	725	65.04
2	605	54.57	865	81.06	730	62.32
20% 3	660	75.82	840	100.94	740	94.49
4	580	65.14	1005	93.56	695	96.51
5	470	52.28	900	93.63	775	88.67
Average Value	585	61.82	890	90.57	735	81.81
Standard Deviation	70	09.37	70	08.12	30	16.88

Appendix E

The Arrangement of The Compressive Strength Data File Used in The Statistical Analysis

1[a]	1[b]	4400[c]
1	1	4830
1	1	4470
1	1	4340
1	1	4040
2[d]	1	4080
2	1	4090
2	1	3570
2	1	3790
2	1	3790
3[e]	1	3620
3	1	3650
3	1	3150
3	1	2680
3	1	3320
4[f]	1	3930
4	1	4050
4	1	4240
4	1	4180
4	1	4050
1	2[g]	4490
1	2	4210
1	2	4540
1	2	5020
1	2	3240
2	2	4540
2	2	4580
2	2	3900
2	2	3870
2	2	3530
3	2	3670
3	2	4310
3	2	4640
3	2	3560
3	2	4050
4	2	5290
4	2	4940
4	2	5060
4	2	4860
4	2	5050
1	3[h]	4340
1	3	4360
1	3	4580

Appendix E (Continue)

The Arrangement of The Compressive Strength Data File Used in The Statistical Analysis

1	3	4770
1	3	4210
2[i]	3	3950
2[i]	3	4160
2[i]	3	4120
2[i]	3	3690
2[i]	3	4160
3	3	3540
3	3	4250
3	3	3990
3	3	3540
3	3	3670
4	3	3950
4	3	3750
4	3	2490
4	3	2890
4	3	2940

[a]Five-percent of aggregate substitute

[b]Plastics waste aggregate

[c]Compressive strength of the tested sample

[d]Ten-percent of aggregate substitute

[e]15% of aggregate substitute

[f]20% of aggregate substitute

[g]Glass waste aggregate

[h]Fiberglass waste aggregate

[i]One of the five tested specimens of this concrete composite at that aggregate percent.

Appendix F

The Arrangement of The Splitting Tensile Strength Data File Used in The Statistical Analysis

1[a]	1[b]	540[c]
1	1	365
1	1	395
1	1	450
1	1	455
1	1	420
2[d]	1	375
2	1	415
2	1	505
2	1	400
2	1	450
2	1	420
3[e]	1	480
3	1	440
3	1	495
3	1	355
3	1	465
3	1	450
4[f]	1	330
4	1	425
4	1	455
4	1	465
4	1	470
4	1	480
1	2[g]	605
1	2	505
1	2	550
1	2	420
1	2	470
1	2	420
2	2	510
2	2	460
2	2	485
2	2	495
2	2	475
2	2	460
3	2	490
3	2	360
3	2	455
3	2	390
3	2	465
3	2	445

Appendix F (Continue)

The Arrangement of The Splitting Tensile Strength Data File Used in The Statistical Analysis

4	2	495
4	2	470
4	2	455
4	2	510
4	2	515
4	2	475
1	3[h]	610
1	3	495
1	3	440
1	3	500
1	3	450
1	3	475
2[i]	3	505
2[i]	3	475
2[i]	3	450
2[i]	3	560
2[i]	3	475
2[i]	3	545
3	3	520
3	3	485
3	3	440
3	3	450
3	3	505
3	3	470
4	3	475
4	3	460
4	3	490
4	3	520
4	3	450
4	3	415

[a]Five-percent of aggregate substitute

[b]Plastics waste aggregate

[c]Tensile splitting strength of the tested sample

[d]Ten-percent of aggregate substitute

[e]15% of aggregate substitute

[f]20% of aggregate substitute

[g]Glass waste aggregate

[h]Fiberglass waste aggregate

[i]One of the six tested specimens of this concrete composite at that aggregate percent.

Appendix G

The Arrangement of The Modulus of Rupture Data File Used in The Statistical Analysis

1[a]	1[b]	955[c]
1	1	820
1	1	935
1	1	1055
1	1	955
2[d]	1	800
2	1	860
2	1	800
2	1	755
2	1	790
3[e]	1	655
3	1	660
3	1	640
3	1	600
3	1	695
4[f]	1	640
4	1	665
4	1	715
4	1	640
4	1	515
1	2[g]	800
1	2	870
1	2	1020
1	2	1010
1	2	845
2	2	920
2	2	955
2	2	850
2	2	810
2	2	835
3	2	780
3	2	880
3	2	850
3	2	765
3	2	835
4	2	860
4	2	875
4	2	870
4	2	1015
4	2	940
1	3[h]	760
1	3	865
1	3	790

Appendix G (Continue)

The Arrangement of The Modulus of Rupture Data File Used in The Statistical Analysis

1	3	810
1	3	870
2[i]	3	840
2[i]	3	770
2[i]	3	850
2[i]	3	835
2[i]	3	730
3	3	795
3	3	730
3	3	705
3	3	705
3	3	785
4	3	760
4	3	765
4	3	775
4	3	730
4	3	780

[a]Five-percent of aggregate substitute

[b]Plastics waste aggregate

[c]Modulus of rupture of the tested sample

[d]Ten-percent of aggregate substitute

[e]15% of aggregate substitute

[f]20% of aggregate substitute

[g]Glass waste aggregate

[h]Fiberglass waste aggregate

[i]One of the five tested specimens of this concrete composite at that aggregate percent.

Appendix H

The Arrangement of The Modulus of Elasticity Data File Used in The Statistical Analysis

1[a]	1[b]	105.91[c]
1	1	50.87
1	1	109.17
1	1	126.66
1	1	104.38
2[d]	1	59.00
2	1	74.53
2	1	53.77
2	1	84.25
2	1	81.68
3[e]	1	57.18
3	1	61.05
3	1	68.72
3	1	68.38
3	1	56.44
4[f]	1	61.31
4	1	54.57
4	1	75.82
4	1	65.14
4	1	52.28
1	2[g]	88.03
1	2	55.08
1	2	83.40
1	2	55.40
1	2	76.33
2	2	55.76
2	2	69.74
2	2	63.12
2	2	58.00
2	2	66.10
3	2	88.36
3	2	89.00
3	2	85.19
3	2	60.53
3	2	87.88
4	2	83.68
4	2	81.06
4	2	100.94
4	2	93.56
4	2	93.63
1	3[h]	70.85
1	3	102.02
1	3	70.69

Appendix H (Continue)

The Arrangement of The Modulus of Elasticity Data File Used in The Statistical Analysis

1	3	84.76
1	3	79.69
2[i]	3	108.41
2[i]	3	66.33
2[i]	3	109.03
2[i]	3	90.49
2[i]	3	80.37
3	3	120.81
3	3	80.70
3	3	72.59
3	3	58.78
3	3	118.43
4	3	65.04
4	3	62.32
4	3	96.49
4	3	96.51
4	3	88.67

[a]Five-percent of aggregate substitute

[b]Plastics waste aggregate

[c]Modulus of elasticity of the tested sample

[d]Ten-percent of aggregate substitute

[e]15% of aggregate substitute

[f]20% of aggregate substitute

[g]Glass waste aggregate

[h]Fiberglass waste aggregate

[i]One of the five tested specimens of this concrete composite at that aggregate percent.

Appendix I1 (see Table 18)

Final Results Obtained From Tukey HSD Procedure on f'c for The Control and New Cementitious Concrete Composites Containing 5% Aggregate Substitutes

Composite	Glass 5%	Plastics 5%	Fiberglass 5%	Control
f'c (psi)	4300	4416	4452	5334
Glass 5%				*
Plastics 5%				*
Fiberglass 5%				*

Appendix I2 (see Table 20)

Results Obtained From Tukey HSD Procedure on Compressive Strength for The Control and New Cementitious Concrete Composites Containing 10% Aggregate Substitutes

Composite	Plastics 10%	Fiberglass 10%	Glass 10%	Control
f'c (psi)	3864	4016	4084	5334
Plastics 10%				*
Fiberglass 10%				*
Glass 10%				*

Appendix I3 (see Table 22)

Results Obtained From Tukey HSD Procedure on Compressive Strength for The Control and New Cementitious Concrete Composites Containing 15% Aggregate Substitutes

Composite	Plastics 15%	Fiberglass 15%	Glass 15%	Control
f'c (psi)	3284	3798	4046	5334
Plastics 15%				*
Fiberglass 15%				*
Glass 15%				*

* means that a significant difference is identified between the composite in the row and the corresponding composite in the column.

Appendix I4 (see Table 24)

Results Obtained From Tukey HSD Procedure on Compressive Strength for The Control and New Cementitious Concrete Composites Containing 20% Aggregate Substitutes

Composite $\underline{f'_c}$ (psi)	Fiberglass 20% 3204	Plastics 20% 4090	Glass 20% 5040	Control 5334
Fiberglass 20%		*	*	*
Plastics 20%			*	*
Glass 20%				

Appendix I5 (see Table 28)

Results Obtained From Tukey HSD Procedure on (T) for The Control and New Cementitious Concrete Composites Containing 5% Aggregate Substitutes

Composite $\underline{T}$ (psi)	Plastics 5% 438	Glass 5% 495	Fiberglass 5% 495	Control 563
Plastics 5%				*
Glass 5%				
Fiberglass 5%				

Appendix I6 (see Table 30)

Results Obtained From Tukey HSD Procedure on (T) for The Control and New Cementitious Concrete Composites Containing 10% Aggregate Substitutes

Composite $\underline{T}$ (psi)	Plastics 10% 428	Glass 10% 481	Fiberglass 10% 502	Control 563
Plastics 10%				*
Glass 10%				*
Fiberglass 10%				

* means that a significant difference is identified between the composite in the row and the corresponding composite in the column.

Appendix I7 (see Table 32)

Results Obtained from Tukey HSD Procedure on (T) for The Control and New Cementitious Concrete Composites Containing 15% Aggregate Substitutes

Composite	Glass 15%	Plastics 15%	Fiberglass 15%	Control
T (psi)	434	448	478	563
Glass 15%				*
Plastics 15%				*
Fiberglass 15%				

Appendix I8 (see Table 34)

Results Obtained from Tukey HSD Procedure on (T) for The Control and New Cementitious Concrete Composites Containing 20% Aggregate Substitutes

Composite	Plastics 20%	Fiberglass 20%	Glass 20%	Control
T (psi)	438	468	487	563
Plastics 20%				*
Fiberglass 20%				*
Glass 20%				

Appendix I9 (see Table 38)

Results Obtained From Tukey HSD Procedure on (R) for The Control and New Cementitious Concrete Composites Containing 5% Aggregate Substitutes

Composite	Fiberglass 5%	Control	Glass 5%	Plastics 5%
R (psi)	819	878	909	944
Fiberglass 5%				
Control				
Glass 5%				

* means that a significant difference is identified between the composite in the row and the corresponding composite in the column.

Appendix I10 (see Table 40)

Results Obtained From Tukey HSD Procedure on (R) for The Control and New Cementitious Concrete Composites Containing 10% Aggregate Substitutes

Composite	Plastics 10%	Fiberglass 10%	Glass 10%	Control
R (psi)	801	805	874	878
Plastics 10%				
Fiberglass 10%				
Glass 10%				

Appendix I11 (see Table 42)

Results Obtained From Tukey HSD Procedure on (R) for The Control and New Cementitious Concrete Composites Containing 15% Aggregate Substitutes

Composite	Plastics 15%	Fiberglass 15%	Glass 15%	Control
R (psi)	650	744	822	878
Plastics 15%		*	*	*
Fiberglass 15%			*	*
Glass 15%				

Appendix I12 (see Table 44)

Results Obtained From Tukey HSD Procedure on (R) for The Control and New Cementitious Concrete Composites Containing 20% Aggregate Substitutes

Composite	Plastics 20%	Fiberglass 20%	Control	Glass 20%
R (psi)	635	762	878	912
Plastics 20%		*	*	*
Fiberglass 20%			*	*
Control				

* means that a significant difference is identified between the composite in the row and the corresponding composite in the column.

Appendix I13 (see Table 48)

Results Obtained From Tukey HSD Procedure on (E) for The Control and New Cementitious Concrete Composites Containing 5% Aggregate Substitutes

Composite	Control	Glass 5%	Fiberglass 5%	Plastics 5%
E (Ksi)	67.31	71.65	81.60	99.40
Control				
Glass 5%				
Fiberglass 5%				

Appendix I14 (see Table 50)

Results Obtained From Tukey HSD Procedure on (E) for The Control and New Cementitious Concrete Composites Containing 10% Aggregate Substitutes

Composite	Glass 10%	Control	Plastics 10%	Fiberglass 10%
E (Ksi)	62.54	67.31	70.65	90.93
Glass 10%				*
Control				
Plastics 10%				

Appendix I15 (see Table 52)

Results Obtained From Tukey HSD Procedure on (E) for The Control and New Cementitious Concrete Composites Containing 15% Aggregate Substitutes

Composite	Plastics 15%	Control	Glass 15%	Fiberglass 15%
E (Ksi)	62.35	67.31	82.19	90.26
Plastics 15%				
Control				
Glass 15%				

* means that a significant difference is identified between the composite in the row and the corresponding composite in the column.

Appendix I16 (see Table 54)

Results Obtained From Tukey HSD Procedure on (E) for The Control and New Cementitious Concrete Composites Containing 20% Aggregate Substitutes

Composite	Plastics 20%	Control	Fiberglass 20%	Glass 20%
E (Ksi)	61.82	67.31	81.81	90.57
Plastics 20%				*
Control				
Fiberglass 20%				

* means that a significant difference is identified between the composite in the row and the corresponding composite in the column.