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An analysis of reinforced concrete composites utilizing recycled polyethylene terephthalate thermoplastic

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An analysis of reinforced concrete composites utilizing recycled polyethylene terephthalate thermoplastic

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University of Northern Iowa, 1991

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AN ANALYSIS OF REINFORCED CONCRETE COMPOSITES UTILIZING RECYCLED POLYETHYLENE TEREPHTHALATE THERMOPLASTIC

A Dissertation
Submitted
In Partial Fulfillment
of the Requirements for the Degree
Doctor of Industrial Technology

Approved:

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December 1991

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ABSTRACT

Removing plastic from landfills does not solve the solid waste problem entirely. Plastic products are difficult to recycle because, unlike aluminum or glass, the plastics used in food packaging cannot be reused for the same purpose. Among the commonly used plastic resins, polyethylene terephthalate (PET) has been widely adopted by the packaging industry. This research study was concerned with recycling of PET thermoplastic in concrete as a way to reduce the volume of solid waste.

Current surveys of recycling efforts reveal that existing PET recycling approaches have become inadequate. Solid waste management is stressing the eminent need for new recycling technologies that may provide a broader perspective than is known today. One solution may be found in concrete, the most used of all construction materials, and one that has rarely been exposed to the ongoing plastic revolution.

Development of a theoretical base, coupled with recognition of certain assumptions and limitations, led to a research design which formulated the PET's role as a reinforcing agent in pavement and floor concrete composites. The focus was on the specific size, volume, and quality of the PET material. The commercially available PET chips used varied in their outside dimensions with width measuring from 1/32" to 1/4", length 1/32" to 1/2", and thickness remaining

constant at 1/64". The research was conducted with plain concrete of type I design mix in a control group, and in four different PET concrete composite experimental groups.

The division among experimental groups was both quantitative and qualitative, as the content of PET governed. Effect of PET quantity was observed on two different volume fractions with content of 0.1% or 1.0% of PET respectively. The effect of PET quality was measured on two different grades; contaminated PET, labeled "as received," and solvent "washed" chips.

The ACI and ASTM Standards were followed in laboratory testing. A 28-day curing period was selected for all 75 concrete specimens. Subsequently, a "three test program" comprised of 25 flexural, 25 splitting tensile, and 25 compressive strength tests, was conducted.

The research outcome revealed that the introduction of PET aggregate in concrete composite is feasible. The various additions of PET did not deliver any significant changes in the value of flexular and splitting tensile strengths. Also, a moderate increase in compressive strength with a higher content of "washed" PET was observed. The potential for industry-wide adoption remains, and the need for possible on-site research is strongly suggested to confirm this study's findings.

Dedicated to my mother
Mrs. Vera Vaverkova-Skalska
who taught me the meaning of quality work.

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CHAPTER I

THE PROBLEM

Introduction

Concrete composites are the most widely used manufactured material of today. On the basis of known world trends, the projected future of concrete looks even more promising, since, for most structural applications, it offers very suitable engineering properties at a low cost, combined with energy conservation aspects and ecological benefits (White, 1977).

In general, concrete is a combination of aggregate, cementing material, and water. The aggregate may consist of different proportions of fine and coarse gravel. About three-quarters of the volume of a concrete mix, according to Pollack (1988), is aggregate; the remaining is a paste made from the cementing material and water. Cement is the chemically active constituent but its reactivity is only brought into effect on mixing with water (Dhir & Jackson, 1989). Furthermore, the aggregate plays no part in chemical reactions but, its usefulness arises because it is an effective and economical filler material. Dhir and Jackson also stated that aggregate provides good resistance to volume changes which take place within the concrete after mixing, and it improves the durability of concrete.

In this research study, the term concrete refers to portland cement (see Definition of Terms) concrete, which is a composite material that is formed from a hardened mixture of type I portland cement (see Definition of Terms), water, fine and coarse aggregates, air, and often other admixtures (Kosmatka & Panarese, 1988; W. F. Smith, 1986). Concrete properties depend on the characteristics of solidified cement, aggregates, and effects of porosity (C. O. Smith, 1986).

Also, the ratios of the various components of the mix, the curing rate, moisture content, temperature, hydration, etc., have an effect upon physical properties of concrete. In almost all instances, Pollack (1988) observed that a decrease of the water-to-cement ratio will increase the physical properties of concrete. The strength of the concrete increases as the cement content increases and as the voids in the concrete decrease.

The importance of the direct link between strength of concrete and the water-cement ratio, providing that the concrete mix is prepared properly, is explained in length by Wilson (1984):

> More water will result in less strength, less water in greater strength. For a given water-cement ratio in a concrete mixture, the strength at a certain age is predictable, assuming that the mixture is plastic and workable, aggregates are strong, clean and sound, and the proper curing care is taken. Too much water results in diluted paste and a weak and porous concrete when it hardens. Not enough results in a mix that cannot be properly placed and finished. Cement paste made with the correct amount of water has strong binding qualities, is watertight and durable. If the cement paste and the aggregates are strong and durable, the concrete is strong and durable. If the cement

> paste is watertight, the concrete is watertight. Strength, durability, freeze-thaw resistance, watertightness, and wear-resistance of the paste, and therefore the concrete, are largely controlled by a sufficiently low ratio of water to cement. (p. 210)

Concrete materials have a high compressive strength (see Definition of Terms), probably the most important physical property of concrete (Mehta, 1986). Therefore, compressive strength can be used as an index for other properties, i.e., tensile or flexural strengths (see Definition of Terms). The tensile strength of a concrete composite is approximately one-eighth its compressive counterpart. For this reason, Mehta stated that concrete is rarely designed for load in tension except when prestressed. Pollack (1988) further pointed to existing disproportion between tensile and compressive strengths, which will cause concrete to fail at the surface when subjected to oscillating loads.

The flexural strength of a concrete composite is usually about one-tenth its compressive strength. Pollack (1988) stated that this particular property of concrete is crucial when it is to be used in beams, slabs, floors or highways where heavy loads may occur. The modulus of elasticity (see Definition of Terms) is generally about 4×10^6 PSI and increases as the curing process continues.

Consequently, tensile reinforcements in the concrete's (see Definition of Terms) crucial areas of the structural sections have to be considered, as reasoned by Nawy (1985) and Schlenker (1970), to compensate for the weak-tension behavior in the concrete component. If the required ingredients are correctly proportioned and mixed, the finished concrete composite becomes a stronger and longer-lasting product. Furthermore, in combination with some type of reinforcing method (C. O. Smith, 1986; Cowan & Smith, 1988), the product can be suitable for use as a main member of many structural systems.

Another intricate dilemma of a cement based composite is its brittle characteristic which could be more noticeable under tensile stress situations or impact loading conditions. In the past few decades, there has been some concern about the performance of the embedded fibers in fiber reinforced cement based materials, as reported by Hannant (1978), and numerous research undertakings have sought to improve the toughness and effectively increase the tensile properties of such composites.

The scientific principles behind the understanding of how different fibers (i.e., steel, glass, asbestos, nylon, cellulose, or polypropylene) incorporated into basic concrete, prevent brittleness or breaking, has only recently been studied, understood, and rationally applied (Neville, 1981). Likewise, natural fibers are sometimes successfully utilized in the concrete matrix. According to Swamy (1984) and Magdamo (1988), in countries where man-made fibers are not easily obtained, the research work and actual constructions have used various native natural vegetable fibers such as abaca, coconut, sugarcane, bamboo, jute, flax, and sisal for reinforcing purposes.

In order to satisfy the rigorous performance requirements of these numerous fiber reinforcement applications, adequate material properties must be achieved (Mehta, 1986; Pollack, 1988) and testing standards met (ASTM, 1983a; ASTM, 1983b; ASTM, 1983c; ASTM, 1983d; ACI, 1983). The reinforcement, provided by randomly distributed fibers, is an appropriate approach to reduce unwanted brittleness, and for improving the highly desirable toughness and tensile strength of newly developed concrete composites. These discussed enhancements have delivered encouraging results already. In their writings Wu and Jones (1987) and Kuilman (1988a), documented the successful performances of the aforementioned fiber reinforced concrete composites.

This particular research work was primarily focused on the analysis of polyethylene's role as a reinforcing agent in concrete composites. The initial idea, with some preliminary research outcomes, was introduced at the 91st Annual Meeting of the American Ceramic Society by Fahmy, Egger, and Varzavand (1989). Also, this research project was directed to utilize specific size and volume of the recycled polyethylene terephthalate thermoplastic (PET) chips as aggregates that have been prepared from recyclable plastic products.

Appropriate testing methods and techniques for the concrete composites, as governed by the American Concrete Institute (ACI) and American Society for Testing and Materials (ASTM) Standards, were closely observed throughout the entire research project.

Statement of the Problem

The focus of this research study was to analyze the flexural, splitting tensile (see Definition of Terms), and compressive strengths of the various concrete composite formulations utilizing the recycled polyethylene terephthalate thermoplastic as a reinforcing material in the concrete matrix.

Purpose of the Study

The purpose of this research study was to provide additional information and knowledge with respect to reinforced concrete composites using recycled PET. Therefore, the main objectives were as follows:

1. To develop an improved matrix of concrete composite by utilizing recycled PET aggregates obtained from used packaging containers for reinforcements.

2. To demonstrate how volume content of PET in the concrete mix can affect the generally accepted material engineering properties and ACI and ASTM Standards.

3. To examine the current fiber and generally reinforced-concrete technology and to establish whether these principles also apply to PET concrete composites.

4. To investigate the concept that PET aggregates used as a ductile material in a brittle matrix can result in an anticipated reinforcement of the concrete composite with quasi-ductile properties that are significantly different from those of regular concrete.

In summary, the general purpose of this research study was to determine the behavior of concrete specimens reinforced with PET aggregates when aged 28 days and then subjected to non-reversed loading.

Need for the Research

The need for the research was twofold:

1. To design and thoroughly test and analyze concrete composites utilizing recycled PET. The research findings may provide insight into a better understanding of the state of the art in concrete, as well as provide some fundamental data to future researchers who will be interested in a concise treatment of this particular technology. Considerable evidence is now available to show that no other research work on the discussed subject has been published, with the exception of cited Fahmy, Egger, and Varzavand's (1989) pioneering work.

2. To expose a different school of thought toward the curbing of plastic scrap. Since PET packaging alone is now

approaching a billion pounds per year production, as revealed by E. I. Du Pont De Nemours & Co., Inc. (Subramanian, 1989), the numerous recycling processes are getting more attention in scientific and general public circles.

It should be emphasized here that the waste plastics once discarded can follow one of two main paths, disposal or recycling. In either case, the first step is waste collection, usually done as part of the municipal waste stream, where plastic is in fact not one material, but a wide range of materials or resins (The National Association for Plastic Container Recovery, 1989). The different properties of these resins make some more suited than others to making a certain product. With its excellent permeability barrier properties, physical properties, and relatively inexpensive manufacturing, PET has become the material of choice for the world-wide packaging industry, particularly for disposable container applications (Resource Recycling, 1990).

Hence, an effective reduction in the quantity of solid waste through plastics recycling (see Definition of Terms) is suddenly becoming a growing industry itself (Curlee, 1986). Concrete composites utilizing recycled PET were viewed by this researcher, and his advisor, as being a unique attempt in the partial solution of the complexity of emerging ecological problems. The following statement is in full support of this research study's intentions:

> . . . we all know that solid waste is a natural concern that's growing larger all the time. We also know that packaging, and plastic packaging in particular is receiving much of the emphasis, even though is represents only 4% of the waste stream currently sent to landfills. We firmly believe that plastics recycling has a definite role to play in the nation's solid-waste management system. (Callari, 1988, p. 21)

Research Questions and Hypotheses

The engineering properties of the analyzed concrete composites, expressed by their flexural, splitting tensile and compressive strengths, became instrumental in the formulation of the projection of the outcome (ACI, 1983).

		Recycled PET Aggregate Quality		
		"as received"	"washed"	
Recycled PET Aggregate Quantity	0.1%	$\mu_{AR.1}$ n=5	$\mu_{W.1}$ n=5	$\mu_{.1}$
	1.0%	μ_{AR1} n=5	μ_{W1} n=5	μ_{1}
		μ_{AR}	μ_{W}	

Where: μ_i = experimental groups mean

n = experimental groups sample size

This study adopted the applied research methodology approach in pursuing answers to the following arrangement of the questions:

Question 1

Research question: Is there a difference between the performance of "as received" and "washed" recycled PET aggregates (effect of PET quality) when used in experimental concrete composites as measured in terms of three ASTM test methods; flexural, splitting tensile, and compressive strengths tests?

Research hypothesis: It is hypothesized that "washed" PET will perform better than "as received" recycled PET quality when used as aggregates in experimental concrete composites and measured in terms of three ASTM test methods; flexural, splitting tensile, and compressive strengths tests.

Null hypothesis:

$H_O: \mu_{AR} = \mu_W$

Question 2

Research question: Is there a difference between the performance of 1.0% and 0.1% volume recycled PET aggregates (effect of PET quantity) when used in experimental concrete composites as measured in terms of three ASTM test methods; flexural, splitting tensile, and compressive strengths tests?

Research hypothesis: It is hypothesized that 1.0% PET will perform better than 0.1% volume recycled PET quantity when used as aggregates in an experimental concrete composites and measured in terms of three ASTM test methods; flexural, splitting tensile, and compressive strengths tests.

Null hypothesis:

$H_O\colon \mu_{1} = \mu_{.1}$

Question 3

Research question: Is there an interaction between the quality and quantity of recycled PET aggregates when used in experimental concrete composites as measured in terms of three ASTM test methods; flexural, splitting tensile, and compressive strengths tests?

Research hypothesis: It is hypothesized that the difference between the performance of 1.0% and 0.1% volume recycled PET content in the experimental groups (effect of PET quantity) will be larger in "washed" than "as received" recycled PET quality when used as aggregates in concrete composites and measured in terms of three ASTM test methods; flexural, splitting tensile, and compressive strengths tests.

Null hypothesis:

$H_O\colon (\mu_{W1} - \mu_{W.1}) = (\mu_{AR1} - \mu_{AR.1})$

Question 4

Research question: Is there a difference in performance between the plain concrete (control group) and four experimental groups of the PET reinforced concrete composites as measured in terms of three ASTM test methods; flexural, splitting tensile, and compressive strengths tests?

Research hypothesis: It is hypothesized that each experimental group of the PET reinforced concrete composites will be superior to plain concrete (control group) as measured in terms of three ASTM test methods; flexural, splitting tensile, and compressive strengths tests.

Null hypothesis:

H_O: $\mu_C = \mu_{AR.1} = \mu_{W.1} = \mu_{AR1} = \mu_{W1}$

Where: μ_C = "control group" mean

Assumptions

In this study, certain assumptions were considered that served as the basis for the ensuing analysis:

1. It is assumed that controlled laboratory conditions, with respect to concrete specimens preparation, handling and curing, were fully observed.

2. It is assumed that the test concrete mix and PET chips were uniformly distributed throughout the testing samples; as the nature of concrete is complex, a concrete composite is not a simple solid, but is a heterogeneous mixture of solids and gels (Neville, 1971).

3. It is assumed that the basic concrete material being tested was representative of other materials in its class.

4. It is assumed that the inaccuracies and wear characteristics of the laboratory testing equipment were not to the extent to impair the results of the proposed tests.

Furthermore, it is assumed that the apparatus and instrumentation was calibrated to accuracies within the standards acceptable for this research study.

5. It is assumed that all material used was consistent and of good quality.

6. It is assumed that the cause/effect relationship of using the PET aggregates as a reinforcing agent in concrete composite could be decided in a laboratory environment by specimen testing.

Limitations

The following limitations were inherent in the research study:

1. The study was limited to the deficiency of prior research work and data in the literature published.

2. The study was limited to the application of one type of design concrete mix, utilizing portland cement type I as the main cementitious material.

3. The study was limited to the use of concrete cylinder specimens of the size 3" diameter x 6" long (Nasser & Kenyon, 1984), and flexural beam specimens of 2" square x 12" long, which were used as samples for testing and the consequent statistical treatment and evaluation.

4. The study was limited to the use of varying sizes of recycled PET chips as aggregates which were randomly oriented in the concrete composite mix. The PET chips dimensions varied as follows: (a) width from 1/32" to 1/4";

(b) length from 1/32" to 1/2"; and (c) thickness was uniform at 1/64".

5. The study was limited to the incorporation of recycled PET aggregates in the concrete composite at two different volume fractions: (a) a volume fraction of 0.1% as suggested by Fahmy, Egger, and Varzavand (1989); and (b) an "inquisitive" volume fraction of 1.0%.

6. The study was limited to the utilization of two kinds of recycled PET aggregates: (a) PET chips contaminated with some foreign substances, i.e., adhesives, special coatings, sugar and torn paper labels from various recycled bottles, these chips were marked "as received"; and (b) PET chips shredded from recycled bottles and specially cleaned, this aggregate was labeled "washed."

7. The study was limited to the concrete composite specimens cured for a 28-day period, and to all required specifications as designated by the ASTM (1983a) Standards.

Definition of Terms

The following is a list of definitions for the terms used in this dissertation.

Compressive Strength

> Maximum stress a material can sustain under crush loading. The compressive strength of a material that fails by shattering fracture can be defined within fairly narrow limits as an independent property. However, the compressive strength of materials that do not chatter in compression must be defined as the amount of stress required to distort the material an

> arbitrary amount. Compressive strength is calculated by dividing the maximum load by the original cross-sectional area of a specimen in a compression test. (Instron, 1987, p. G2)

Flexural Strength

1. "The outer fiber stress developed when a material is loaded as a simply supported beam and deflected to a certain value of strain" (Budinski, 1983, p. 22).

2. "An alternate term is modulus of rupture" (Instron, 1987, p. G4).

Modulus of Elasticity

> Under simple stress within the proportional limit, the ratio of stress to corresponding strain is called the modulus of elasticity. This term is somewhat of a misnomer, since it refers to stiffness in the elastic range rather than to elasticity. Under tensile stress, this measure of stiffness is sometimes called Young's modulus, after the English physicist who first defined it. (Davis, Troxell, & Wiskocil, 1964, p. 40)

Plastics Recycling

> 1. Recycling is a broad term which covers the whole range of activities beginning with the collection of waste materials, separation of its various components, and reprocessing them back to their original condition or converting them to energy. It is already a complex problem because of the many different types of material involved.
> . . . the complexity of the problem, polyethylene wastes alone consists of several varieties including high density, high density - high molecular weight, low density and linear low density. (Glenn, 1989, p. 1)
>
> 2. The vast majority of work in the area of plastics recycling has been focused on technological issues, and many of the technical problems that once prevented the recycling of plastic wastes have now been overcome. However, the degree to which plastics recycling has been adopted in the market place has, at best, been disappointing.
> . . . the first step is usually some form of separation, followed by one of the four main types of

> recycling - primary, secondary, tertiary or quaternary recycling. In primary recycling, the waste plastic is usually melted and recycled into a product that has characteristics equivalent to those of the original product.
>
> . . . because very little contamination can be tolerated with primary recycling, contaminated manufacturing wastes, sometimes called manufacturing nuisance plastics, and virtually all postconsumer plastic wastes cannot be recycled in primary sense.
>
> . . . secondary recycling, the product made from the waste plastics may have physical and chemical characteristics that are inferior to those of the original product. Examples of secondary products are fence posts, drainage gutters and compressed plastic sheets or boards that can be used in much the same way as lumber. Secondary plastic products are usually large and bulky and are normally made by melting or softening thermoplastic wastes and reforming the mixture into the desired shape.
>
> Tertiary recycling utilizes waste plastics to produce basic chemicals and fuels and has received a great deal of attention in recent years. Tertiary processes, such as pyrolysis and hydrolysis, can accommodate the recycling of numerous resins and, depending upon the particular process, can be used to recycle plastics as a segregated waste or as a part of the municipal waste stream.
>
> Quaternary recycling involves the retrieval of the plastic's heat content by burning and, like some forms of tertiary recycling, can make use of plastics either in, or segregated from, the municipal waste stream. The Btu values of different resins vary, but in general yield about 12,000 Btu per pound, or about the same as anthracite coal on a per pound basis.
>
> A major, if not the major, obstacle to the technical and economic feasibility of plastics recycling is the degree of waste contamination and the possibilities for decontaminating the waste with different separation processes. (Curlee, 1986, pp. 335-338)

3. The U.S. Environmental Protection Agency classifies a material as "recycled" if it is used, reused, or reclaimed in accordance with 40 CFR 261.1(c)(7). Furthermore, a material is "used or reused" if it is either employed as an ingredient (including its use as an intermediate) to make a

product; however, a material will not satisfy this condition if distinct components of the material are recovered as separate end products (as when metals are recovered from metal containing secondary materials), or employed in a particular function as an effective substitute for a commercial product as governed by 40 CFR 261.1(c)(5). Also, a material is "reclaimed" if it is processed to recover a useful product or if it is regenerated. Examples include the recovery of lead values from spent batteries and the regeneration of spent solvents as indicated in 40 CFR 261.1(c)(4) (Environmental Protection Agency, 1990, p. 28).

4. In this study it is emphasized that the use of recycled PET thermoplastics in concrete composites can afford a low cost alternative to plastics recycling in general. There are, however, many ideas to combine existing, known, and proven technologies with creative options. This research is exploring a unique combination/ approach to develop concrete composites using recycled PET aggregate in their matrix and consequently, is offering a considerable reduction in unwanted solid waste PET volume.

Portland Cement

> By far the most important of the inorganic cementing materials is portland cement. Portland cement is a synthetic material made by calcining carefully controlled mixtures of claylike and lime-bearing materials. The claylike materials furnish SiO_2 and the calcined mass consists principally of silicates of

calcium. Since Portland cement sets and hardens by reaction with water, it is a hydraulic cement. (Keyser, 1968, p. 273-274)

Splitting Tensile Strength

1. The splitting cylinder tensile strength test (ASTM C 496) can be used to determine the first crack tensile strength, but should not be used for additional determinations because of unknown stress distributions after the first crack. (American Concrete Institute, 1983, p. 6)

2. The relationship between splitting tensile strength and direct tensile strength or modulus of rupture has not been determined. The split cylinder tensile test has been used in production applications as a quality control test, after relationships have been developed with other properties when using a constant mixture. (American Concrete Institute, 1988, p. 588)

Tensile Reinforcement in the Concrete

Concrete is extremely weak in tension but stronger in compression; the steel reinforcing placed into reinforced concrete takes all of the tensile load placed upon the structure. The purpose of reinforcement always being the improvement of strength properties. Reinforcements may involve the use of a dispersed phase, or strong fiber, thread, or rod. (Schlenker, 1970, p. 338)

Tensile Strength

1. Resistance of a material subjected to tensile loading. A test for determining the behavior of materials under axial tension loading is known as a tensile test. In a tensile test, the specimen is gripped from its two ends and pulled apart. (Kazanas, Klein, & Lindbeck, 1988, p. 385)

2. The ratio of the maximum load in a tension test to the original cross-sectional area of the test bar. (Budinski, 1983, p. 21)

Type I Portland Cement

Type I portland cement is a general-purpose cement suitable for all uses where the special properties of other types are not required. It is used in concrete

> that is not subject to aggressive exposures, such as sulfate attack from soil or water, or to an objectionable temperature rise due to heat generated by hydration. Its uses in concrete include pavements, floors, reinforced concrete buildings, bridges, railway structures, tanks and reservoirs, pipe, masonry units, and other precast products. (Kosmatka & Panarese, 1988, p. 15)

CHAPTER II

REVIEW OF RELATED LITERATURE

Introduction

Professional journal articles, published research findings, and specialized books concerned with various fiber reinforced concrete composites, polyethylene properties and applications, and contemporary PET thermoplastic recycling technologies were primarily researched and studied for meeting the objectives of this particular review. As of today, composite materials are among the oldest and newest of materials (Clauser, 1975). Also, fiber reinforced concretes already have many significant uses in the real world of construction and industry, as there has been growing improvements in flexural and tensile strengths, impact resistance, and in the reduction of crack developing tendencies and propagation.

Fiber Reinforced Concrete Composites

Usually, fiber reinforced concrete is composed of portland cement concrete and a variety of fibers. The fibers are also available in many shapes, i.e., round, flat, crumpled, and deformed, with typical lengths of 0.25 to 3 inches, and thicknesses ranging from 0.0002 to 0.030 inch (Kosmatka & Panarese, 1988).

The American Concrete Institute Committee 544 (1986) provided the following definition of fiber reinforced concrete:

> Fiber reinforced concrete is concrete made of hydraulic cements containing fine or fine and coarse aggregate and discontinuous discrete fibers.
> Continuous mesh, woven fabrics, and long rods are not considered to be discrete fiber type reinforcing elements. . . . (pp. 544.1R-1-544.1R-2)

Since concrete is a nonelastic material, with nonlinearity behavior starting at a very early stage of loading, only the ultimate strength approach is considered for the comparison. Hannant (1978) pointed out that there is a great temptation under these circumstances to add reinforcing fibers to any existing mix and try to compare the new product with the existing concrete.

Mixing and compaction problems will occur if a "reasonable" quantity of fibers, as suggested by Hannant (1978), is added to the usual proportion of aggregates. Such reinforced concrete composite may then be rejected as too difficult to produce or handle. Hannant explained that this particular practice has led to the R&D of designs which will accept appropriate amounts of a specific fiber type. In addition, this will give acceptable compaction characteristics and later on, in the hardened state, should provide desirable engineering properties.

It should be stressed that the additional strength fiber reinforcement for concrete (primarily in tension), depends on the compatibility of the materials to act together in resisting the external forces. In principle, the reinforcing agent (PET thermoplastic in this research study) has to undergo the same strain and deformation as the surrounding concrete in order to avoid the discontinuity and unwanted separation of the prime composite materials under load. Therefore, the mechanical properties of the mentioned reinforcement material should complement the basic concrete in order to improve the finished product to meaningful testing parameters (American Concrete Institute Committee 544, 1986).

Hence, as a rule these fibers must be ductile, strong in tension, and capable of bonding to the cement paste. For instance, materials such as natural fibers, steel, asbestos, and polypropylene have been used widely and successfully. Kuilman (1988b) offered the following outlook on fiber reinforced concrete performance:

> The added element of fiber in concrete has introduced a new flexibility to concrete design and construction. This new design dimension is particularly useful for industrial floors, where large concrete expanses meet stringent performance requirements. The problem most commonly encountered with reinforcing steel and wire mesh - improper placement - does not occur with fiber. The fibers are dispersed throughout the concrete matrix during the mixing phase and can therefore be expected to perform consistently. (p. 64)

Most mentioned fibers are available in a variety of dimensions, and have somewhat different properties when added to concrete composite. However, under certain conditions some fibers can also act as secondary reinforcers. When the design stresses are moderate, the fibers can be effective in resisting tension stresses in areas of greatest load (Kuilman, 1988a).

Since "high fiber contents" deliver noticeable improvements in mechanical properties producing unworkable concrete composite, and "low fiber contents" in workable concrete give no appreciable improvements in properties, practical concrete is a compromise at "moderate fiber contents". Tattersall and Banfill (1983) stated that typical concrete mixes should use 0.8-1.5% fiber volume, and water reducing admixtures and/or pulverized fuel ash for maintaining workability. Furthermore, typical mix proportions are recommended 1:(0.4-0:6):(2-3):(0.8-1.5) by weight of cement:water:sand:fiber aggregate.

In theory, the fibers interlock and entangle around aggregate particles and the concrete mix becomes more cohesive and less likely to segregate. The size and concentration of aggregate in fiber reinforced concrete has a critical influence on the effect of the fibers. According to Tattersall and Banfill (1983), as the size of the fiber increases it becomes more difficult to achieve uniform dispersion, because the fibers are "bunched" into the concrete fraction, which can move freely past the fibers and around the stones during compaction.

For composite material such as fiber reinforced concrete, the mechanical behavior depends not only on the properties of the fiber and the concrete, but also on the bonding between them. It should be understood that the nature of the bonding interface in any cement based systems is somewhat complicated because there may be chemical reactions between the cement and some types of fiber. Additionally, the nature of the interface may keep changing with time as the cement matures (Mindess & Young, 1981).

Many fiber reinforced concrete's failures happen due to bond failure--fiber pull out. The bond strength can be improved, as observed by Hannant (1978), by deforming the fibers in various ways (if possible). However, large changes in the bond strength are not reflected by similar changes in the concrete strength, but will improve the post-cracking behavior. Hannant emphasized that a very good bond may increase tensile strength, absorption, and the overall durability of the concrete.

The technology and use of fiber reinforced concrete is still developing. The controlling factor of such concrete application is not only its material properties but the cost. Fibers are an additional cost in concrete composites, however, when the extra material cost can be justified, fiber reinforced concrete can be used in a variety of applications.

For instance, steel fiber reinforced concrete has been used successfully for pavements highway, and runway overlays, to reduce excessive material cracking and also thickness. Asbestos fibers have long been used for pipes and fire-resistance products, while glass fibers have been utilized by spray-on cladding on buildings to deliver both structural and architectural qualities (White, 1977).

Polypropylene fibers were first incorporated as an admixture to concrete in 1965 for the construction of blast-resistant buildings for the U.S. Corps of Engineers. The early works with polypropylene fiber in concrete were supported by Shell International Chemical Company who provided the material under the trade name Caricrete. This pioneering work has been recorded by Zonsweld (1976) who explained the principles and circumstances behind the early applications.

When industry achieved the production of polypropylene with adequate properties, its use in concrete was made possible by fibrillation of film around the longitudinal splits. Such prepared polypropylene film as commented by Hannant (1978), was cut to the required lengths and used as a main reinforcing material. Kuilman's (1988a) recommended portion of 1.5 pound per cu. yd. of concrete is estimated to contain approximately 300 fibers per cu. inch. Because there are so many fibers in any given cu. inch, polypropylene fibers need not be very strong or have much bond to be effective. These fibers, according to Kuilman, cannot increase the allowable tension of the concrete, therefore, the suggested quantity of polypropylene is about 1.0-1.6 lb/cu. yd. of concrete.

Even though considerable advancement has been made with polypropylene fibers in concrete composites, it is evident that more research needs to be done in this field. One of the latest findings is reported by Fahmy, Lovata, and Varzavand (1989) who incorporated chemical treatment of polypropylene fiber surfaces in a mild linear alcohol base solution prior to the concrete mixing operation. The data obtained from compressive, splitting tensile, and flexural strength tests indicated that after the 45-day curing period, there was noticeable improvement in all mentioned static strength properties.

Polyethylene Terephthalate

A synthetic material closely resembling linear polyethylene was made and studied just before 1900, but it was produced from an expensive material (diazomethane), so the discovery had no commercial results. Schwartz and Goodman (1982) described the real beginning of polyethylene through an incidental discovery during a high pressure process in 1933 England by Fawcett and Gibson. The material produced turned out to be the insulation needed for World War II radar defenses which Britain was developing at that time. In 1940 production was about 100 tons, and by the end of the war the capacity was 1,500 tons per year. During the

WWII years, polyethylene production by British technology was undertaken in the U.S.A.

Polyethylene is the major member of a group of chemical compounds known as polyolefins. Today, it is one of the most widely used polymers of any of the thermoplastic materials. Processable by all known thermoplastic production methods, as explained by Kresser (1969), polyethylene is noted for its flexibility, low-temperature impact resistance, and many other favorable physical properties.

Polyethylenes are broadly divided into low-density (PET) and high-density (HDPE) variants. According to Beck (1980), low-density materials exhibit branching of the chain, which minimize the degree of crystallinity possible and, hence, the spaces between the molecules cause a low density. Such low-crystalline, low-density polyethylene is flexible, transparent to translucent, and has lower maximum temperature range than does high-density polyethylene. As of today, low-density polyethylene finds use in many applications, especially, in the soft drink beverage bottles market.

Baird and Baird (1982) summed up the general properties of polyethylene as follows:

1. Very tough at low temperature.
2. Excellent chemical resistance.
3. High permeability to air and gasses.
4. Low in water vapor transmission.
5. Fairly high mold shrinkage.

6. Flexibility is good to excellent, even to 100 deg. F.
7. Weatherability is fair, can be improved by adding carbon black.
8. Excellent electrical insulating properties.
9. Easily colored in transparent (film), translucent or opaque material.
10. Odorless and tasteless. (p. 30)

The PET material for processing is supplied in crystalline pellet form. Prior to injection molding, PET must be dried in a high-temperature type desiccant dryer. Seymour (1975) stated that the moisture content of pellets after drying should be less than 0.005% to minimize hydrolytic breakdown (molecular chain cleavage) and loss of properties. Molding material should be free from contamination to produce tough, clear preforms that comply with applicable FDA regulations. To produce PET bottles, Nitschke and Sami (1989) offered the following description of the manufacturing process:

> . . . the amorphous preforms, or parisons, are reheated to a temperature just above the glass transition temperature (Tg) of the polymer and blown under high pressure into container molds. The stretching of the parison wall, as it conforms to the geometry of the mold, results in biaxial orientation - a high level of molecular chain alignment and extension that results in increased molecular order and improvement in physical and gas barrier properties.
> . . . Tensile yield strength, and creep resistance of the polymer are vastly improved as a direct result of the orientation process. The improved creep resistance of oriented containers made from PET is a major factor in the success of these containers for packaging highly pressurized carbonated beverages. (p. 45)

Stretch-blow molding grades of unfilled PET (virgin polymer without any additives of fillers added) are available in clear, green, and amber colors. Nitschke and Sami (1989) observed that "reactor colored polymers improve color uniformity without the need for additional secondary compounding that can adversely affect physical properties" (p. 45). Additional key properties of a typical product molded from unfilled PET material are (Juran, 1989, p. 623):

Tensile strength (at break)	7,000-10,500 PSI
Elongation (at break)	30-300%
Compressive strength (rupture)	11,000-15,000 PSI
Flexural strength (rupture)	14,000-18,000 PSI
Tensile modulus	400,000-600,000 PSI
Flexural modulus (73 deg. F)	350,000-450,000 PSI
Izod impact (ASTM D256A)	0.25-0.70 Ft.-lb.
Hardness (Rockwell)	M94-101
Specific gravity	1.29-1.40
Water absorption (24 hrs.)	0.1-0.2%

In summary, PET thermoplastic is chemically inert, non-corrosive and has a high resistance to salts, oils, and many different industrial chemicals. Furthermore, PET as a material is very stable and does not absorb water. It was the Fahmy, Egger, and Varzavand (1989) study that recognized the suitability of PET thermoplastic for reinforced concrete application. According to their findings, PET chips used as an aggregate, and randomly dispersed in the concrete composite, can prevent the microcracks phenomenon from developing and minimize crack propagation.

Consequently, this described mechanism can result in raising the flexural strength of such concrete composites and improving the overall resistance to spalling, abrasion, cavitation, and even to impact. Similar behavior is noticed when various fiber concrete formulations were applied as was also observed by Kuilman (1988a).

PET Application and Recycling

Plastic products are beneficial due to their extensive use by the human population. For instance, the plastics revolution has produced the safest, lowest cost food delivery system known. It has provided major advances in health, transportation and consumer products, and the revolution will continue to evolve, as more and more plastics are retrieved from the waste stream and returned to useful, long-lived purposes. Therefore, recyclability is repeatedly the criteria leading to product purchase (Huntley, 1989).

In general, the solid waste disposal dilemma (as with most of societies problems) will be solved by professionals with the proper planning, skills and knowledge, to develop new technologies. This view is supported by Freeman (1988) who stated:

> While nonprofessional finding and insights often are important in achieving professional solutions, in the end it is professionalism that sets things right. Yet, achieving solid waste disposal solutions differs markedly from solving other societal problems. For one thing, everybody is - and ought to be - a player in the quest for solid waste disposal solutions. We are all affected by the problem, and, indeed each of us contributed to causing the problem in the first place. (p. 5)

Naber (1988) explained that plastics were relatively nonexistent in the packaging industry in the 1970s, but today they include more than 5% of the waste stream. About two million tons of plastic packaging is created in the U.S.A. annually, and most of that material ends up in the solid waste dumps. Naber argued that while plastic may be convenient for consumers, it creates headaches for recyclers and municipalities interested in savings landfill capacity. Removing plastic from landfills does not solve the solid waste problem entirely.

Plastic products are difficult to recycle because, unlike aluminum or glass, the plastics used in food packaging cannot be reused for the same purpose (Food and Drug Administration, 1989). It should be stressed that plastic resins, synthetic materials made from oil and natural gas that are combined in a polymerizing process, are designed to have a certain molecular makeup that if commingled during recycling would cause the resins to lose the unique qualities that make them valuable materials.

About 11% of all discarded packaging materials of today consists of plastic as bottles or other rigid containers and film wraps and bags (Sacks, 1990). However, bottles provide the most readily collected and washed source, mainly PET thermoplastic bottles used for carbonated beverages. During 1989, according to Sacks, the Plastic Institute of America estimated that about 250 million pounds of such bottles were recovered for reuse. Sacks also reported an additional sharp increase in the volume of PET bottles consumption and consequent collection over the next two years.

Since products of PET thermoplastic are utilized by human for food-contact application (Food and Drug Administration, 1989), future demand is expected to be enormous, i.e., the need to handle pickled food, edible oil, spices, and many other food ingredients. Also, new colors are attracting and increasing the popularity of PET material for the packaging of pharmaceutical, cosmetic, and toiletry products. The plastic technology forecasters see, therefore, another production "explosion" of PET in the immediate future with unavoidable growth in needs for various recycling technologies (Morrow & Merriam, 1989).

From a material handling perspective PET bottles are superior in many ways over their glass counterparts. For instance, a filled two-liter PET beverage bottle weighs 24% less than comparable product using glass. When empty, it weighs one-tenth as much as a typical glass container of the same volume. These favorable parameters, as pointed out by Nitschke and Sami (1989), are affecting labor cost, energy, and cost savings throughout the entire handling and distribution network, from the original manufacturers to the end users. For this very reason, PET materials have captured nearly 100% of the two-liter soft drink container market, as well as smaller bottles that are gaining wide acceptance and use at the present time.

According to Nitschke and Sami (1989) the unusual success of PET as a carbonated beverage packaging material is due especially to its toughness and clarity, as well as the development of high-speed bottle production technology and its favorable economics. PET bottles are not only lightweight and shatter-resistant but recyclable with excellent barrier properties.

When sorted, ground, and even cleaned, recycled PET material (primarily obtained from soft beverage bottles) is in limited demand for possible application in geotextiles, carpet fiber, floor tiles, injection molded parts, and various film and sheet materials. Currently, there are commercially available recycled PET bottles in the form of chips/flakes in both, "washed" or "as received" (contaminated) quality.

The cleaning technologies of contaminated PET containers have evolved tremendously. The latest technology is fully automated and extremely efficient, with each unit's handling capacity at about 600 pounds per hour. Whole bottles are automatically decapped (HDPE or aluminum closing caps) and decupped (polypropylene bottom reinforcing cups) prior to the wash process. The PET bottles, even if the residual soft drink is contained, is then shredded to a certain size and put through a solvent/density wash system.

The entire solvent separation system is self contained and the solvent is continuously recycled and reused. This washing removes the labels, adhesives, sugar and all other foreign contaminants present (Fitzell, 1984). The separated HDPE caps together with polypropylene cups are usually shredded and resold to produce new plastic materials (Brewer, 1990).

The most current surveys of the public and private sectors are revealing that all existing PET recycling approaches have become inadequate. Solid waste management is stressing the eminent need for additional recycling technologies that may provide a broader perspective than is known today. Since a number of issues are involved, a solution that is multidisciplinary is needed.

In an attempt to manage the growing waste disposal problem, a number of state governments have mandated their municipalities to recycle at least 20% of their waste by the mid 1990s. Recycling seems to be the most logical approach to waste management, but deciding on the most efficient and affordable program of recycling has become a difficult task.

Despite the American public's clear commitment (Byers, 1990), it is felt that recycling by itself will not solve the nation's solid waste problem (including plastic waste). A clear 48% of the population agree with the idea that any real solution to a community's solid waste disposal problem will have to include recycling as well as incineration or other unknown technologies.

Byers (1990) observed that this is in contrast with many national environmental leaders, who believe that a major commitment to recycling will not demand the need for new incinerators. However, the recycled PET may be burned without harmful by-products as its high caloric value makes it attractive in supporting combustion in industrial and municipal incinerators.

Increasing plastic recycling depends on the availability of a variety of recycling technologies, including more sophisticated approaches capable of recovering a wider range and larger quantity of resins from the mixed plastics stream typical of municipal solid waste (Brewer, 1990). Therefore, full benefits from the discussed PET reinforced concrete can be obtained only when the PET's true function in these concrete composites is researched and verified. The main effort of this study is to contribute to the body of knowledge in this field.

Summary

There were two major objectives of this review of literature and, of course, of the whole research project. The first was to study the suitability and performance of recycled PET material in concrete composite. The second objective was to investigate the present status and immediate future developments in plastic recycling because the projections indicate (Curlee, 1986; Naber, 1988; Huntley, 1989; Morrow & Merriam, 1989; Sacks, 1990; Byers, 1990) that the total quantity of plastic waste will continue to rise during the upcoming decade.

According to Curlee's (1986) estimates, 47 billion pounds of plastic waste is expected in 1995. Postconsumer waste will grow more rapidly than manufacturing waste and by 1995 should comprise about 92% of the total. While packaging (including PET products) will remain the largest single source of plastic wastes, plastics from the construction sector will grow most rapidly in percentage terms.

To make a sizable dent in the solid waste stream, recycling programs must go more aggressively after plastics that occur in large volumes, and certainly the PET market is one of them. Hence, this research on PET reinforcing behavior in concrete composites has looked at the existing solid waste situation from this point of view.

Today, "change" is the central word in society's thinking, when new technologies and methods are being transformed at an accelerated pace world-wide. PET concrete composite technology should be considered a part of this latest phenomenon.

During this investigation of related literature, the only cataloged piece of directly associated research pertaining to the PET utilization as aggregate in concrete composites was mentioned in Fahmy, Egger, and Varzavand's (1989) project. Moreover, it should be noted that the conservative construction industry has a reputation for accepting technological change slowly. This research study could also be seen as a positive contribution toward assistance in this direction.

CHAPTER III

METHODOLOGY

The PET Reinforced Composite Definition

Preparation of fiber reinforced concrete, according to the American Concrete Institute (1986), can be accomplished by more than one method. The same logic should apply to the PET reinforced concrete researched in this study:

> The choice of method will depend on the job requirements and the facilities available; that is plant batching, ready-mixed concrete, or hand mixing small quantities in the laboratory. Above all, it is necessary to have a uniform dispersion of the fibers and prevent the segregation or balling of the fibers during mixing. (p. 544.1R-7)

Since the PET reinforced concrete composite is a new entity, it was designed and referred to in this research study as a material for pavements and floors. Therefore, the "ready-mix" concrete commonly available in 60 pound bags was adopted for this research.

In general, the pavements and industrial floors demand resistance to impact, dynamic loading, material disintegration, and extensive wear. Particularly where thinner than normal slabs are desired and/or impact resistance to various shocks are demanded. There is a tremendous potential for PET reinforced concrete composite in these specific areas. Concrete utilized for pavements and floors is the most common and large in volumes, therefore a suitable place for recycled PET aggregate.

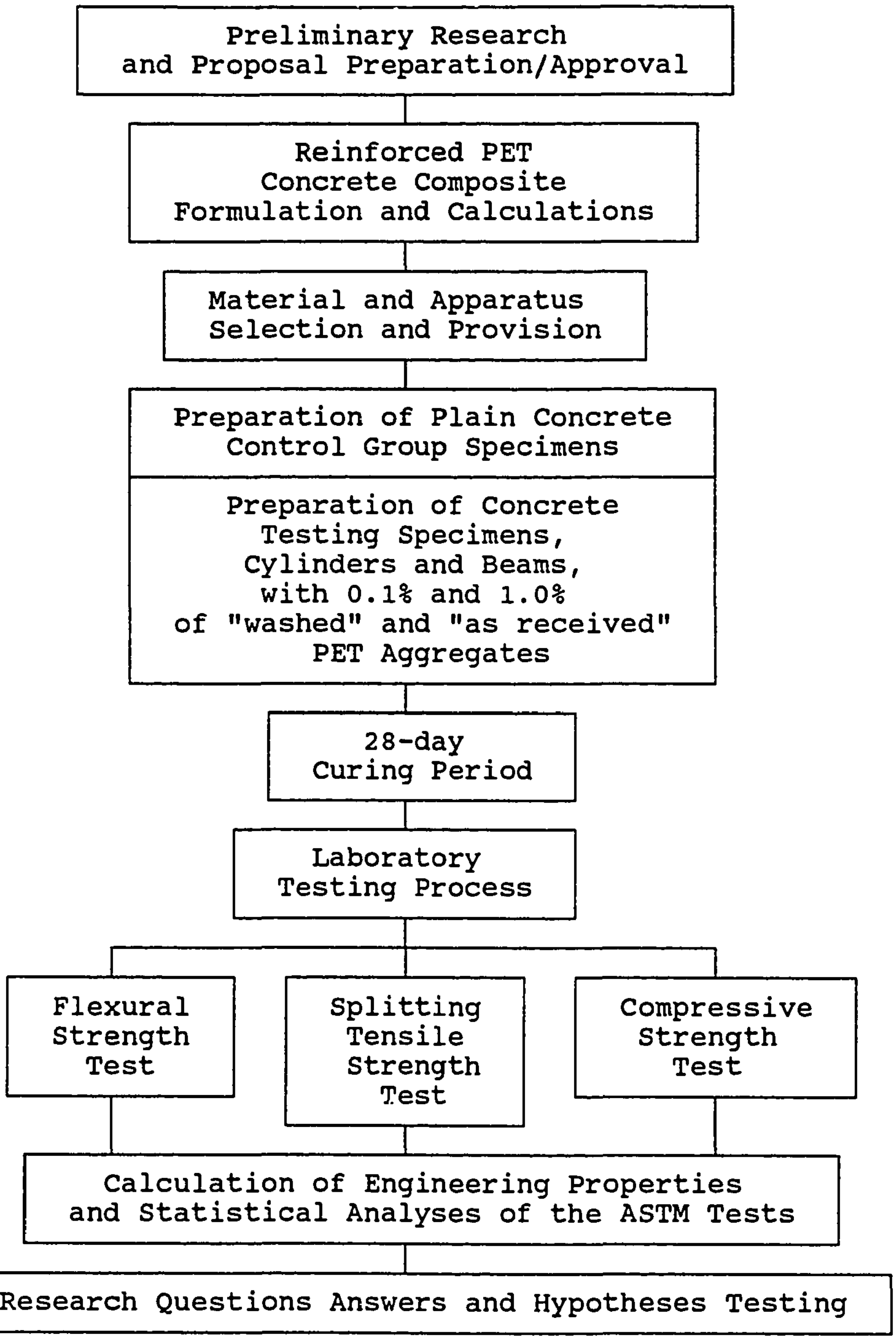
Overall Organization Procedures

The research study was conducted on reinforced concrete composites utilizing recycled PET thermoplastic as an aggregate. The results of selected tests was analyzed and compared against those of a control group of plain concrete.

In general, this particular analysis was of the applied research type. Moreover, the whole research process was based on theoretical scientific principles, and generally accepted handling and testing procedures of the American Concrete Institute (ACI) and the American Society for Testing and Materials (ASTM). Also, the experimental procedures applied in this research undertaking were concerned with specifics such as the concrete mix preparation, the methods of investigation, the methods of statistical treatment (including the sample size), and the required laboratory apparatus. The overall organization steps of the conducted research process were captured in Figure 1.

The Sample Preparation and Size

The control group in this research study did not contain any PET recycled material as an aggregate for reinforcement of the concrete matrix. Therefore, these testing specimens were prepared from plain concrete alone. However, the experimental groups were utilizing two different qualities of PET recycled aggregates, "washed" and "as received." Concurrently, the testing groups were



<u>Figure 1</u>. The overall organization of the conducted research process in a schematic representation diagram.

comprised of the following pattern: two reinforced concrete groups consisting of PET aggregate with a volume fraction of 0.1% and 1.0% respectively. Conclusively, three different laboratory tests were performed; flexural strength test (ASTM, 1983b), splitting tensile test (ASTM, 1983c), and compressive test (ASTM, 1983d).

If determination of sample size is based on ASTM (1983a) guidelines, the size of the sample as required by ASTM (3 specimens per batch) is not suitable for the minimum requirements needed for designing a statistical model:

> The number of specimens and the number of test batches are dependent on established practice and the nature of the test program. Guidance is usually given in the test method or specification for which the specimens are made. Usually three or more specimens are molded for each test age and test condition unless otherwise specified. (ASTM, 1983a, p. 140)

Therefore, it was decided to mold five samples for each test group, experimental and control. This procedure was selected to exceed the minimum requirements for the ASTM testing specification, and at the same time, to elevate quality design for the follow up statistical analyses.

In summary, there was a "three test program" consisting of flexural, splitting tensile, and compressive strengths, where each test on concrete composites covered the identical number of specimens:

* Control group (plain concrete)...........	5 specimens
* 0.1% "washed" PET content................	5 specimens
* 1.0% "washed" PET content................	5 specimens

* 0.1% "as received" PET content..........5 specimens

* 1.0% "as received" PET content..........5 specimens

Total 25 specimens

Hence, there were 25 specimens prepared and tested in each test or a total of 75 specimens in the described three test series.

Methods of Investigation

As seen on the schematic diagram (Figure 1), three primary means of investigation were employed. Since this was applied research of an experimental nature concerning the design and behavior of reinforced PET concrete composites, the investigation was conducted by strictly observing the three ASTM testing methods (ASTM, 1983a, 1983b, & 1983c).

Flexural Strength Testing

The first measure was the investigation of flexural strength of concrete composites. This standard test method requires a center-point loading force applied directly on the specimen which is in the form of a simple beam (ASTM, 1983b). In this case, the actual flexural beam size was 2" square x 12" long. The primary objective of this testing method was to find the calculated values of the flexural strength (R). Then, the test results were compared among the experimental groups and the control group of plain concrete.

Splitting Tensile Strength Testing

The second measure was the investigation of splitting tensile strength properties, in particular, the determination of the first crack tensile strength. According to ASTM (1983c), this method should not be used for additional determinations because of unknown stress distributions after the first crack. Also, the ASTM requires the specimen to be in the form of a cylinder. Due to the suggestions of Nasser and Kenyon (1984), smaller test cylinder of the size 3" diameter x 6" long was adopted in this research.

The main intention of this test was to obtain splitting tensile strength values for the experimental PET reinforced concrete composite groups and then through the statistical treatment, compare those with the results of the governing control sample group.

Compressive Strength Testing

The third method of measurement was the compressive strength test (ASTM, 1983d). This particular test selection is based primarily on wide general acceptance of this method for measurement of the bond strength between the aggregates, including PET aggregates used in this research, and the concrete's paste. The size of compressive specimens were identical to those utilized for splitting tensile strength test, 3" diameter x 6" long concrete cylinders.

The Laboratory Apparatus

As required by the outlined procedures, the following suitable equipment of the University of Northern Iowa, Department of Industrial Technology was available:

* To perform tests on the flexural beams, the Vega Low-Range Non-Metallic Tester, Model 10-K was used.
* To test concrete cylinder properties (splitting tensile strength test and compressive test), the Baldwin Tate-Emery Tester, Type UNIV was employed.

All laboratory test specimens were prepared using external vibration only (ACI, 1983), since internal vibration is not desirable and rodding is not acceptable, as these methods of consolidation may produce PET aggregate orientation and nonuniform samples.

Statistical Methods

The statistical procedures, means and standard deviations were reported for each of the test groups (four experimental groups and one control group). Research hypothesis 1, 2, and 3 were tested with a two-way analysis of variance because of the variable of quality and quantity. Hypothesis 4 was tested with the "Dunnett Method of Multiple Comparisons" (Glass & Hopkins, 1984) to compare the experimental concrete composite groups with the control group.

CHAPTER IV

PRESENTATION OF RESEARCH DATA

Introduction

The focus of this research was to attain a better understanding of the inner nature of pavement concrete composites using recycled PET thermoplastic as a reinforcing agent in the matrix. The study is viewed as contributory to this field of technology because it investigated the unknown behavior and strength limit for concrete composite specimens when subjected to laboratory non-reversed loading.

This new "reuse concept," as presented by this research, may propagate a wider utilization of PET material in inherently brittle concrete. Also, the presented analyses and findings may provide a sound base which can lead to further research work and additional needed knowledge of this reinforcement in specialized concrete composites with quasi-ductile properties that are significantly different from those of plain concrete.

The disclosure of the results of the three selected essential ASTM tests (flexural, splitting tensile, and compressive strengths tests) is discussed in this chapter. The sample size for all mentioned tests was kept uniform with five specimens per tested concrete group in each test which exceeded the minimum requirements for ASTM (1983a) testing specifications. This judgement was supported by the decision to elevate the quality design of the tests' statistical analyses.

This chapter's content covers each of the ASTM test specifications with associated necessary calculations for investigated engineering property and statistical analysis. Moreover, the four research questions, together with their respective hypotheses, were then tested and answered through statistical analysis of the results on specifically related engineering property. The investigation process presented here is based on the actual values of flexural, splitting tensile, and compressive strengths acquired in the laboratory setting.

Flexural Strength Testing

Test Narrative

The standard test method for flexural strength of concrete using a beam with center point loading (ASTM, 1983b) was accepted by this research project. This method is known as a transverse beam test with some other materials. The adoption of this particular testing procedure is based on the American Concrete Institute (1983) recommendation for determining the flexural strength (denoted by the symbol $\underline{R}$). The flexural strength (or modulus of rupture) in normal-weight concrete, as observed by Kosmatka and Panarese (1988), is approximated as 7.5 to 10 times the square root of the compressive strength.

Prior to the curing process, the flexural specimens were cast into beams of 2" square x 12" long. The ASTM (1983b) testing requirements ask for this shape sample, in the form of the described simple beam, because it is the best configuration for adequate quality control and reliable flexural strength analysis and comparison. The specimens (Figure 2) were positioned in the tester in the prescribed

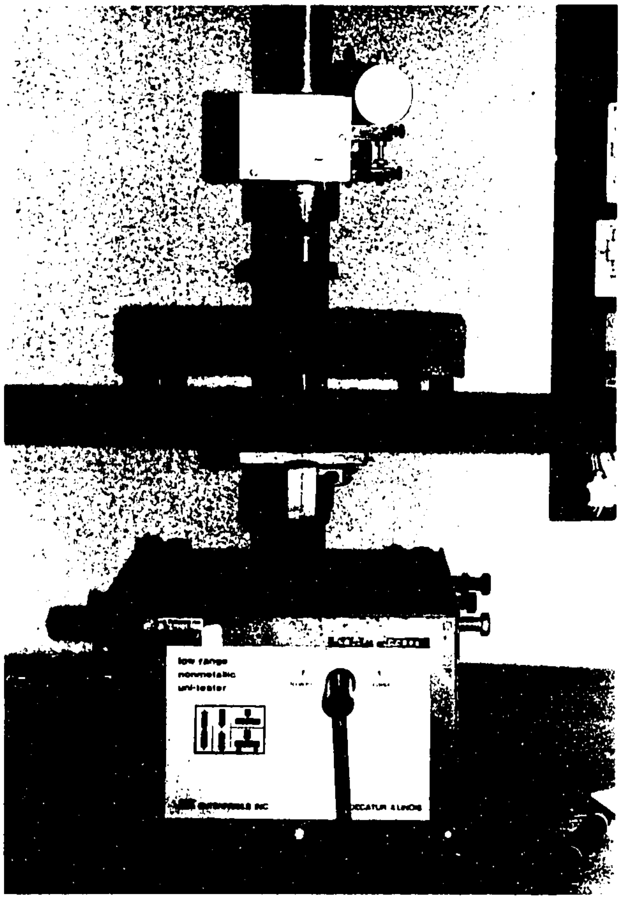


Figure 2. Vega Low-Range Non-Metallic Tester, Model 10-K with a concrete beam in the flexural testing position.

manner, as seen in the photograph of the typical flexural testing arrangement outlined here.

The two lower support points were situated one inch inward from each end of the 12" testing beam. This particular geometry allowed a 10" span, as required by this ASTM test, for the midpoint vertical loading arm equipped with a specially shaped point-end bar.

After removing all free unwanted movements between beam and load/support knife edges, and then indexing the tester's dial load indicator to zero, the testing system was prepared. This setup procedure was staged for all 25 flexural beams tested. In Figure 3, the rupture of the

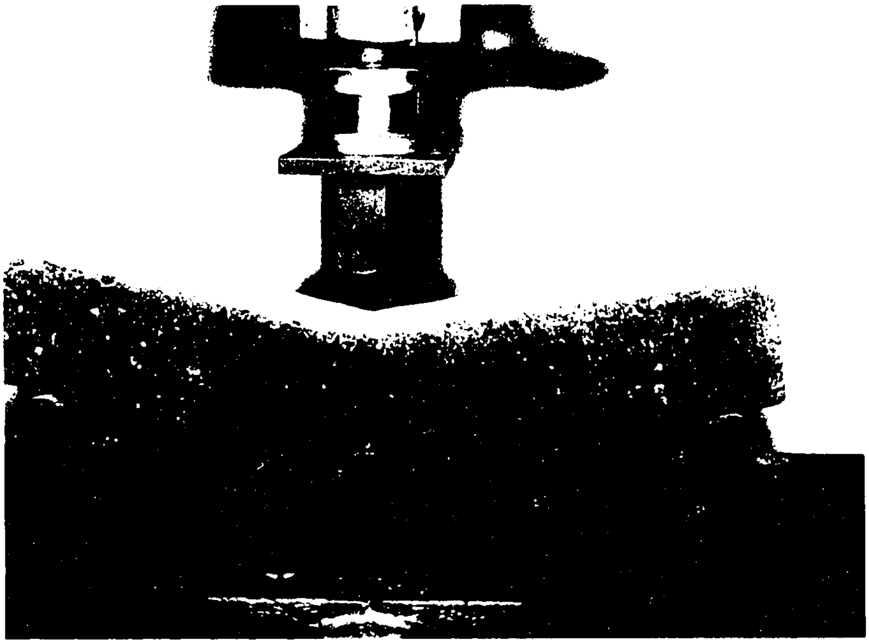


Figure 3. Rupture of beam after flexural strength testing.

flexural beam is shown. The tester's dial indicator was equipped to record load readings directly in pounds, when each dials' increment represented 10 pounds of additional load applied.

Flexural Strength Calculations

All these calculations are concerned with the flexural strength (R) computed for each of the 25 concrete test specimens by using the suggested ASTM (1983b) formula where $R = 3Pl/2bd^2$.

When: R = flexural strength or modulus of rupture (PSI)

P = maximum applied load (lbs.)

l = span length (in.)

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

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

The essential engineering properties, maximum load and flexural strength, obtained from data gathered during the laboratory tests were organized in Table 1. The calculated flexural strength (R) was then statistically treated (Tables 1 through 5), analyzed, and consequently compared with the control group and all experimental PET concrete composite groups.

Statistical Analysis

The values of the calculated flexural strength for all five testing groups (total of 25 flexural strength tests), as presented in Table 1, were prepared for the chosen Minitab's statistical software in the orderly customized arrangement (see Table 2). This fundamental organization matrix served as the "data base" for the computer statistical treatment and analysis.

Where:

Concrete type = 1 = control group (plain concrete)
2 = any experimental concrete group
PET quality = 0 = no content of PET
1 = "as received" PET content
2 = "washed" PET content
PET quantity = 0 = no content of PET
1 = 1.0% of PET volume
2 = 0.1% of PET volume
Sample sequence = 1 to 5 = sample number within each group
R (PSI) = calculated flexural strength in PSI (also splitting tensile or compressive strength)
Composite group = 1 = C = control group
2 = AR1 = 1.0% "as received" PET content
3 = AR.1 = 0.1% "as received" PET content
4 = W1 = 1.0% "washed" PET content
5 = W.1 = 0.1% "washed" PET content

Table 3 is offering the summarized interaction effect between two different qualities ("washed" and "as received") and two different quantities (1.0% and 0.1%) of recycled PET aggregate as had been tested in experimental concrete composites. Table 3 is also includes statistical data, individual group means and standard deviations, obtained from the statistical treatment of the series of performed ASTM flexural strength tests.

The statistical treatment was concerned with two-way analysis of variance on the flexural strength as influenced by the PET quality and PET quantity aggregate content which was used in the experimental concrete composite groups. It should again be mentioned that there were two different qualities, "washed" and "as received," and two different quantities, 0.1% and 1.0% of PET contents tested by this research. The results of a two-way analysis of variance for this engineering property are summarized in Table 4.

Close observation of the results as presented by Table 4 suggests that in the PET quality of all AR and W groups there is no significant mean difference at the .05 level, $\underline{F}$ (1.16) = 2.84, $\underline{p} > .05$. In the bar chart in Table 4, these particular results are also graphically shown at the 95% confidence level with a large overlap.

On the other hand, the PET quantity bar chart shows no overlap among all 1.0% PET groups and all 0.1% PET groups. Here, the findings indicated a considerable mean difference in flexural strength ($\underline{R}$) of the two specified groups and was statistically significant, $\underline{F}$ (1,16) = 14.80, $\underline{p} < .01$.

The interaction between the groups with different quality and quantity of recycled PET aggregates, as they have been affected in all experimental concrete composite specimens, is summarized and exhibited in Table 3 and Table 4. These tables are comparing means and standard deviations obtained from the statistical treatment of the ASTM flexural strength (R) test results expressed in PSI.

It can be interpreted from Table 3 and Table 4 that the best performance was achieved by the AR.1 group ("as received" with 0.1% PET content) with a 712.40 PSI group mean. Based on the contributed data from Table 3 and Table 4, it can be concluded that the analyzed interaction between the quality and quantity of recycled PET aggregates in concrete composites was statistically significant, F (1,16) = 7.86, $p < .05$.

In final analysis, the level of quality between "as received" (total mean 634.60 PSI) and "washed" (total mean 674.00 PSI) concrete composite groups, was apart only 39.40 PSI, which is about 0.51 of the total standard deviation (77.31 PSI). On the other hand, the level of quantity between 0.1% (total mean 699.30 PSI) and 1.0% (total mean 609.30 PSI) showed a larger disproportion between the two observed quantities. The 0.1% PET content performed better than 1.0% quantity PET content contrary to research hypothesis 2. If measured in terms of the total standard deviation, the recorded difference was 90.0 PSI, this is about 1.16 of the total standard deviation (77.31 PSI).

Table 1

Recorded Maximum Loads and Calculated Flexural Strength (R)

Based on the ASTM Flexural Strength Test Results

	Flexural strength tests					
Composite group	1	2	3	4	5	*M*
Control						
Load (lbs.)	420	350	350	415	415	-
R (PSI)	788	656	656	778	778	731.2
AR1						
Load	280	280	340	300	285	-
R	525	525	637	563	534	556.8
AR.1						
Load	360	400	340	425	375	-
R	675	750	637	797	703	712.4
W1						
Load	385	360	340	300	380	-
R	722	675	637	563	712	661.8
W.1						
Load	370	370	345	365	380	-
R	694	694	647	684	712	686.2

Note. Load values provided here are maximum applied loads recorded in pounds prior to the flexural beam rupture.

Table 2

Organization of the Flexural Strength (R) Test Data for Statistical Treatment as Required by the Computer Software Used

Row seq	Concrete type	PET qual	PET qty	Sample seq	R (PSI)	Composite group
1	1	0	0	1	788	1
2	1	0	0	2	656	1
3	1	0	0	3	656	1
4	1	0	0	4	778	1
5	1	0	0	5	778	1
6	2	1	1	1	525	2
7	2	1	1	2	525	2
8	2	1	1	3	637	2
9	2	1	1	4	563	2
10	2	1	1	5	534	2
11	2	1	2	1	675	3
12	2	1	2	2	750	3
13	2	1	2	3	637	3
14	2	1	2	4	797	3
15	2	1	2	5	703	3
16	2	2	1	1	722	4
17	2	2	1	2	675	4
18	2	2	1	3	637	4
19	2	2	1	4	563	4
20	2	2	1	5	712	4
21	2	2	2	1	694	5
22	2	2	2	2	694	5
23	2	2	2	3	647	5
24	2	2	2	4	684	5
25	2	2	2	5	712	5

Note. See p. 50 for the detailed interpretation of the assigned numbers/values in this organization matrix.

Table 3

Flexural Strength (R) as Affected by PET Quality and Quantity Interaction

	PET quantity		
PET quality	0.1%	1.0%	All groups
AR groups			
n	5	5	10
M (PSI)	712.40	556.80	634.60
SD (PSI)	62.74	47.47	97.34
W groups			
n	5	5	10
M	686.20	661.80	674.00
SD	24.13	64.60	47.74
All groups			
n	10	10	20
M	699.30	609.30	654.30
SD	46.89	76.93	77.31

Note. n = experimental groups sample size

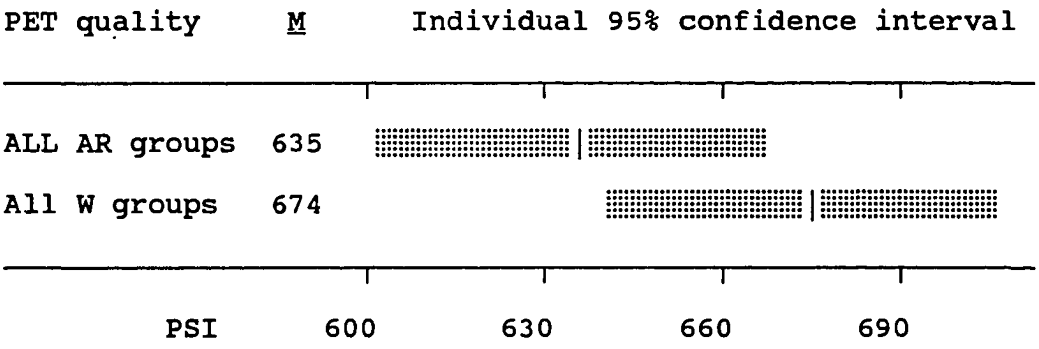
M = experimental groups mean

SD = sample standard deviation.

Table 4

Two-Way Analysis of Variance on Flexural Strength (R)

Source of variation	df	SS	MS	F	p
PET quality	1	7762	7762	2.84	> .05
PET quantity	1	40500	40500	14.80	< .01
Interaction	1	21517	21517	7.86	< .05
Within groups	16	43780	2736		
Total	19	113558			



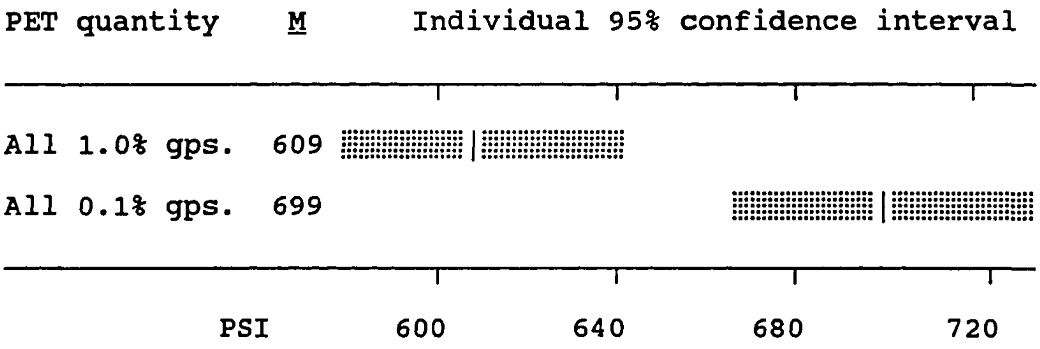
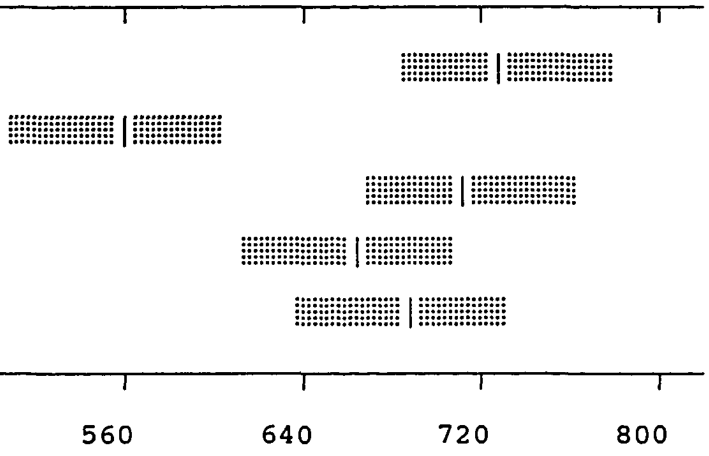


Table 5

Statistical Analysis of Variance on Flexural Strength (R)

Group	*M*	*SD*
C	731.2	68.77
AR1	556.8	47.47
AR.1	712.4	62.74
W1	661.8	64.60
W.1	686.2	24.13

Individual 95% confidence interval for mean based on pooled *SD* = 55.99



Source of variation	*df*	*SS*	*MS*	*F*	*p*
Between gps.	4	93433	23358	7.45	< .001
Within gps.	20	62696	3135		
Total	24	156129			

Note. Sample size (*n*) for all tested concrete groups was 5.

The F-test and analysis of variance were utilized for comparison of the means and standard deviations for all five concrete groups (control group and four experimental groups) to determine statistically significant differences among these groups (see Table 5).

The review of results, as organized and presented by Table 5, indicated that null hypothesis 4 of equality of means should be rejected at the point .001 level. However, as shown in bar graph of Table 5, there was no significant mean difference in flexural strength among the five tested groups, except group AR1 (1.0% "as received" PET content) with a lower group mean of 556.8 PSI. The mean of the AR1 group is more than one pooled standard deviation (55.99 PSI) below the mean of the control group. Therefore, research hypothesis 4 which stated that all experimental groups will be superior to plain concrete (control group) was not supported by the data obtained.

Splitting Tensile Strength Testing

Test Narrative

The splitting cylinder tensile strength test is commonly used to determine the first crack tensile strength (ASTM, 1983c), but should not be utilized for additional interpretations because of unknown stress distributions after the first crack appearance (American Concrete Institute, 1983). The precise identification of the first crack in the split cylinder is generally considered difficult without some introduction of the sophisticated technological means of crack detection. Also, the relationship between splitting tensile strength and direct tensile strength or modulus of rupture has not been determined (American Concrete Institute, 1988).

Nevertheless, the split cylinder tensile technique (Figure 4 and Figure 5) has been widely used in concrete production primarily as a quality control measure when some relationships with other engineering properties have been established. Therefore this common approach of industry was adopted by this research project, including the reduced test

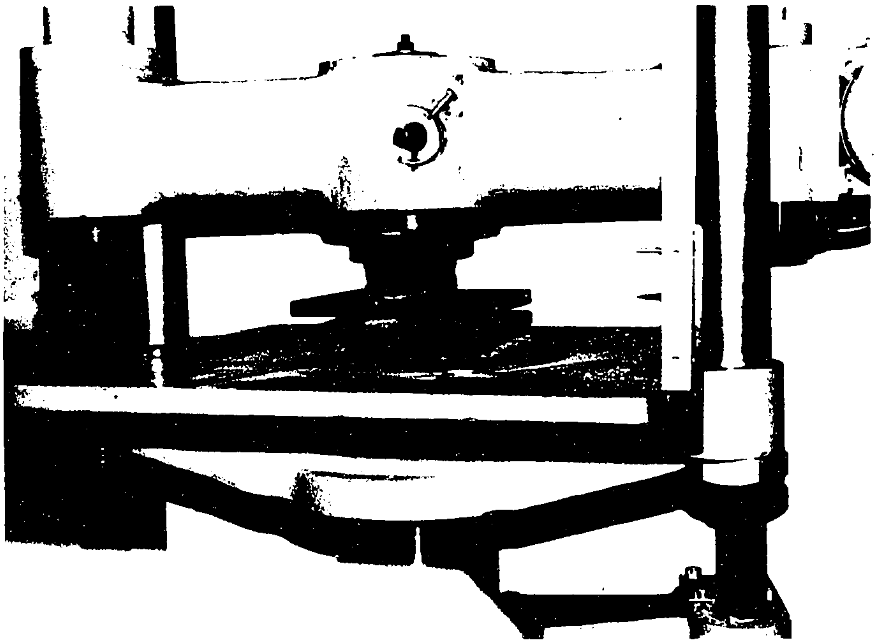


Figure 4. General view of the secured cylindrical concrete specimen prior to splitting tensile strength test.

specimen size. The test specimens of the size 3" diameter x 6" long were prepared in typical, commercially available, waxed paper molds to assure uniform external dimensions of the concrete cylinders. Curing and handling of these specimens were identical to those used for compressive cylinders or flexural beams.

To obtain splitting tensile strength properties, the Baldwin Tate-Emery Tester, Type UNIV was selected. This testing laboratory apparatus is a hydraulically operated piece of machinery which conforms to all requirements of the ASTM Standards. Figure 4 illustrates the splitting concrete

Figure 5. Rupture of the concrete splitting cylindrical specimen.

cylinder arrangement in the initial testing position in accordance with the ASTM (1983c).

The photograph in Figure 4 demonstrates not only the initial testing position, but also the required supplementary items needed for sufficiently securing a concrete cylinder inside the tester. As a bearing plate a 1" thick steel bar was prepared which was complemented by two 1/8" thick x 1" wide plywood bearing strips. Plywood strips were located between the specimen at both the upper tester bearing surface and lower supplemental bearing plate.

The hydraulic load was then applied uniformly at an increasing rate with avoidance of possible shocks until failure of the specimen occurred. The rupture of the concrete cylindrical specimen was captured in Figure 5. The maximum applied loads indicated by the testing machine at the failure point were then recorded.

Splitting Tensile Strength Calculations

The 25 recorded maximum applied loads in pounds were then converted into the splitting tensile strength ($\underline{T}$) values following the ASTM (1983c) formula $\underline{T} = 2P/\pi ld$.

Where: $\underline{T}$ = splitting tensile strength (PSI)

P = maximum applied load (lbs.)

π = pi (3.1416)

l = length of the specimen (in.)

d = diameter of the specimen (in.)

The maximum applied loads together with corresponding splitting tensile strengths (T) were tabulated and are presented in Table 6. Then, calculated splitting tensile strength results were statistically analyzed and investigated in their relationship to the control group and among all experimental PET concrete composite groups.

Statistical Analysis

At first, all 25 recorded maximum loads together with the splitting tensile strength values (T), acquired through the calculations, were summarized individually and in their respective experimental groups. Also, each group's mean was calculated and presented in Table 6. Table 7 provides a prerequisite organizational matrix as demanded by the computerized statistical process. Detailed interpretation of the assigned numbers/values of this particular table can be found on p. 50 of this dissertation. Further statistical data are presented in Table 8, Table 9, and Table 10.

Table 8 summarized and exhibited the interaction effect among quality, "washed" (W), "as received" (AR), and quantity (0.1% and 1.0% recycled PET content) as it had been used in experimental concrete composite groups. This tabulated summary is examining statistical data, individual group means and standard deviations, acquired through the calculation of the series of ASTM splitting tensile strength tests.

The PET quality and PET quantity relationship was exhibited in Table 9 where two-way analysis of variance on the splitting tensile strength _T_ was applied. The review of the attached bar charts revealed significant mean difference at the .05 level. First, the PET quality bar chart shows the mean difference in observed engineering property (_T_) to be about one total standard deviation in its size at the 95% confidence level, which is considered to be statistically significant, _F_ (1,16) = 61.77, $p < .01$. Therefore, null hypothesis 1 was rejected and research hypothesis 1 was supported.

The second bar chart of Table 9, which refers to PET quantity, resembles the results and appearance observed in the previous PET quality analysis. Also here, the graph exhibited a mean difference in the tested performance on the splitting tensile strength property which was recorded about one total standard deviation at the 95% confidence level. This described behavior difference among the PET quantities indicated to be statistically significant, _F_ (1,16) = 58.74, $p < .01$. Therefore, null hypothesis 2 was rejected, however, 0.1% performance was significantly better than 1.0% which contradicted research hypothesis 2 in direction.

The inquiry into Table 8 and Table 9 is also indicating that the level of quality or quantity interaction did not show any persistent pattern. The highest result, if measured by the particular group mean, was attained by the

W1 group with a mean of 419.00 PSI, the second highest mean performance was delivered by the AR.1 experimental group mean of 416.80 PSI, and the third highest by the group W.1 (mean 383.60 PSI). The AR1 (mean 208.80 PSI) was considerably lower than these three groups which was statistically significant, $\underline{F}$ (1.16) = 116.80, $\underline{p} < .01$.

In Table 10 is presented a statistical analysis of variance on splitting tensile strength values ($\underline{T}$) when the $\underline{F}$-test was chosen for comparison of the distribution of means and standard deviations for all tested concrete groups with the main aim being to find out the differences between them. It is noticeable that the control group is showing the strongest performance in splitting tensile strength among all tested groups. The results were statistically significant, $\underline{F}$ (4,20) = 74.78, $\underline{p} < .0005$.

In comparison with other experimental groups, Table 10 also revealed that the AR1 group mean is lagging about four to five pooled standard deviation (one pooled standard deviation 29.94 PSI) behind the rest of the three studied groups. If summarized, there is no significant difference between AR.1, W1, and W.1 test groups but, they are still more than three pooled standard deviations below the mean of the control group.

Table 6

Recorded Maximum Loads and Calculated Splitting Tensile Strength (T) Values

	Splitting tensile strength tests					
Composite group	1	2	3	4	5	M
Control						
Load (lbs.)	16450	14600	15900	13500	14100	-
T (PSI)	582	516	562	477	499	527.2
AR1						
Load	6300	5400	4800	6700	6300	-
T	223	191	170	237	223	208.8
AR.1						
Load	11350	11700	10750	12900	12250	-
T	401	414	380	456	433	416.8
W1						
Load	12300	11400	12850	11100	11600	-
T	435	403	454	393	410	419.0
W.1						
Load	10800	11500	11100	10200	10600	-
T	382	407	393	361	375	383.6

Note. Load values provided here are maximum applied loads which caused the rupture of the concrete specimen.

Table 7

Organization of the Splitting Tensile Strength (T) Test Data for Statistical Treatment as Required by the Computer Software Used

Row seq	Concrete type	PET qual	PET qty	Sample seq	*T* (PSI)	Composite group
1	1	0	0	1	582	1
2	1	0	0	2	516	1
3	1	0	0	3	562	1
4	1	0	0	4	477	1
5	1	0	0	5	499	1
6	2	1	1	1	223	2
7	2	1	1	2	191	2
8	2	1	1	3	170	2
9	2	1	1	4	237	2
10	2	1	1	5	223	2
11	2	1	2	1	401	3
12	2	1	2	2	414	3
13	2	1	2	3	380	3
14	2	1	2	4	456	3
15	2	1	2	5	433	3
16	2	2	1	1	435	4
17	2	2	1	2	403	4
18	2	2	1	3	454	4
19	2	2	1	4	393	4
20	2	2	1	5	410	4
21	2	2	2	1	382	5
22	2	2	2	2	407	5
23	2	2	2	3	393	5
24	2	2	2	4	361	5
25	2	2	2	5	375	5

Note. See p. 50 for the detailed interpretation of the assigned numbers/values in this organization matrix.

Table 8

Splitting Tensile Strength (T) as Affected by PET Quality and Quantity Interaction

	PET quantity		
PET quality	0.1%	1.0%	All groups
AR groups			
n	5	5	10
M (PSI)	416.80	208.80	312.80
SD (PSI)	29.20	27.48	112.84
W groups			
n	5	5	10
M	383.60	419.00	401.30
SD	17.49	24.97	27.59
All groups			
n	10	10	20
M	400.20	313.90	357.05
SD	28.65	113.52	91.94

Note. *n* = experimental groups sample size

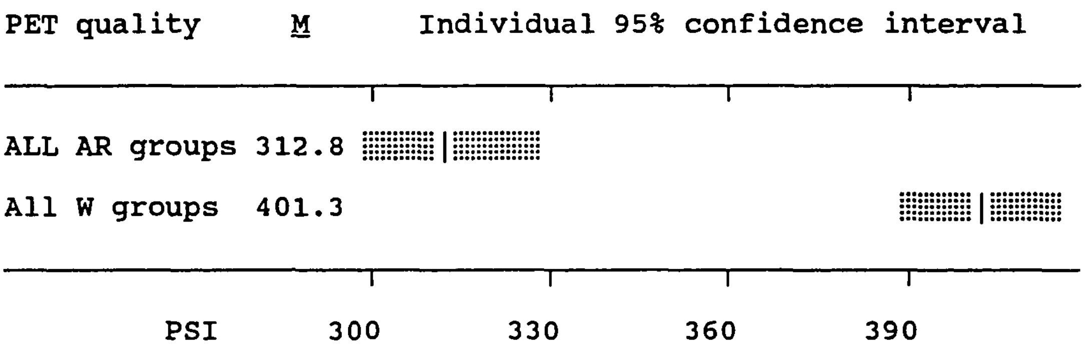
M = experimental groups mean

SD = sample standard deviation.

Table 9

Two-Way Analysis of Variance on Splitting Tensile Strength (T)

Source of variation	df	SS	MS	F	p
PET quality	1	39161	39161	61.77	< .01
PET quantity	1	37238	37238	58.74	< .01
Interaction	1	74054	74054	116.80	< .01
Within groups	16	10149	634		
Total	19	160603			



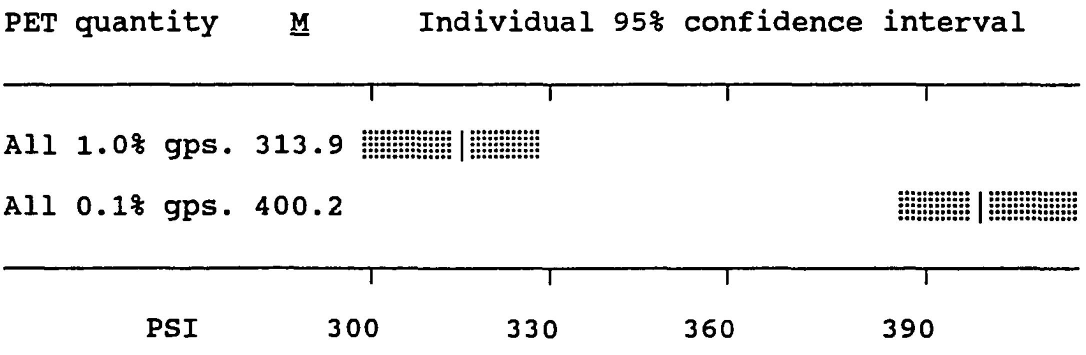
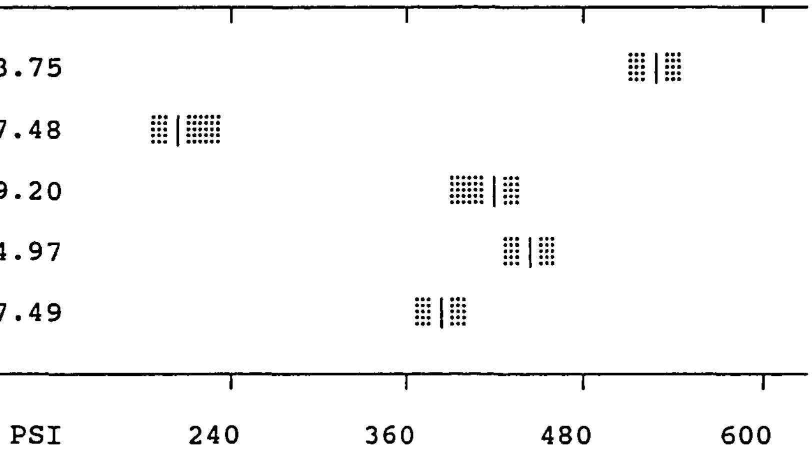


Table 10

Statistical Analysis of Variance on Splitting Tensile Strength (T)

Group	M	SD
C	527.2	43.75
AR1	208.8	27.48
AR.1	416.8	29.20
W1	419.0	24.97
W.1	383.6	17.49

Individual 95% confidence interval for mean based on pooled SD = 29.84



Source of variation	df	SS	MS	F	p
Between gps.	4	266258	66565	74.78	< .0005
Within gps.	20	17804	890		
Total	24	284062			

Note. Sample size (*n*) for all tested concrete groups was 5.

Compressive Strength Testing

Test Narrative

It has been pointed out that compressive strength may be described as the maximum resistance of a concrete to the axial loading forces. Over the years, compressive strength has become a primary physical property used in the engineering calculation of new concrete designs and production (Kosmatka & Panarese, 1988). This property is commonly expressed in pounds per square inch (PSI).

Also, compressive strength is used as an index for other fundamental engineering properties and their interpretation. Although compressive strength is an essential characteristic of concrete, such as wear resistance, durability or permeability. In summary, compressive strength is the most recognized single used measure for the expression of the quality of any type of concrete.

The compressive test of cylindrical concrete specimens is closely governed by ASTM (1983d) guidelines. During the testing period of this research project, the same laboratory apparatus was employed as for the determination of the previously examined splitting tensile strength property, the Baldwin Tate-Emery Tester, Type UNIV. Therefore, all equipment confirmation requirements of the preceding test were fully adopted by the compressive strength testing.

A photograph of the overall compressive strength arrangement with a concrete cylinder being tested is shown in Figure 6.

For uniform stressing of the compression specimen the ends of the cylinder were prepared flat and parallel to each other. Such described geometry did not cause stress concentrations because the specimen's ends were truly perpendicular to the axis of the cylinder. After such preparation arrangement as required by ASTM (1983d), all specimens had been properly cured for a 28-day period and then they were, one by one, located between the tester's compression plates. Also, it should be noted that while

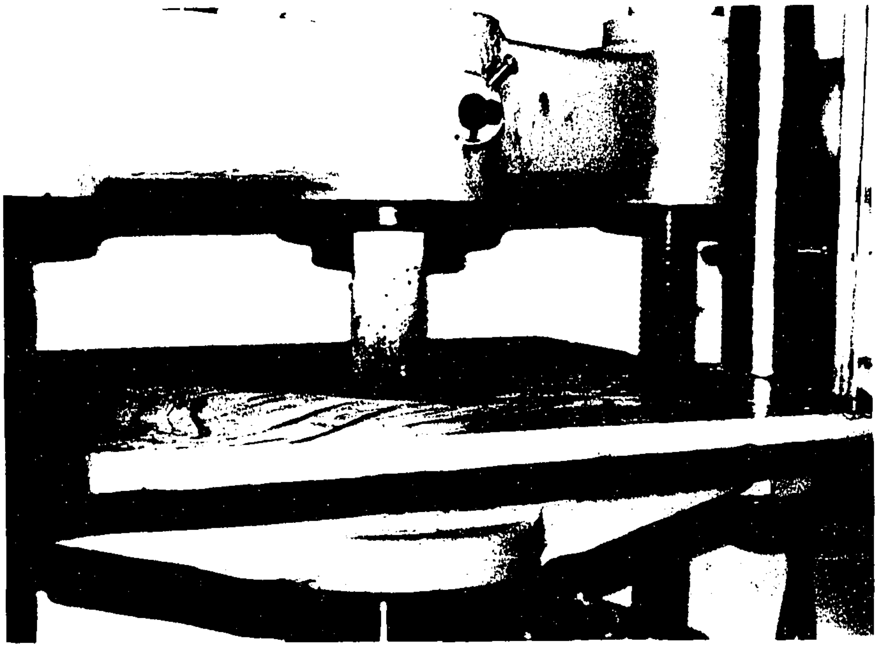


Figure 6. A view of the cylindrical concrete specimen being axially loaded during the compressive strength test.

inserting capping shims, precaution was taken to assure perpendicularity between the bearing surface and the axis of the concrete cylinder test specimen.

Since the speed of testing has a definite affect on the compressive strength behavior (Davis, Troxell, & Wiskocil, 1964) the attention was given to rate of loading. The applied hydraulic load was maintained without shocks until the specimen failed, then the maximum load withstood by the specimen during the test was recorded. Typical cylindrical specimen failure and its appearance is illustrated in the following Figure 7.

Figure 7. Typical failure of the concrete cylindrical specimen immediately after the compressive strength test.

Compressive Strength Calculations

The ASTM (1983d) testing procedures calculate the compressive strength by dividing the maximum load carried by the specimen during the test by the average cross-sectional area. For that reason the diameter of the cylindrical concrete specimen was determined to the nearest 0.01" by averaging the two diameters measured at right angles to each other at about midheight of the specimen. The average diameter was used for acquiring the needed cross-sectional area. Then, the compressive strength for each specimen was calculated from the given equation $\underline{S} = P/A$.

Where: $\underline{S}$ = compressive strength (PSI)

P = maximum applied load (lbs.)

A = cross-sectional area of the specimen (sq. in.)

Using the described formula, the calculated compressive strength values, with their corresponding maximum recorded applied loads, were compiled in Table 11. Furthermore, obtained compressive strength results were then statistically treated and analyzed in their relation to each observed group as is discussed in the following paragraph and related Tables 12 through 15.

Statistical Analysis

As in the two prior analyzed ASTM tests, initial attention was given to the organization of the basic properties obtained through testing. Here, the main concern was on the recorded maximum loads and subsequent calculation of the compressive strength (S). Both these engineering properties, together with each tested group compressive strength mean, were listed in Table 11.

Similar to Table 2 and Table 7, Table 12 was exclusively prepared for Minitab's statistical software. Interpretation of the assigned symbols and their descriptions are available on p. 50 of this research.

Table 13 exhibits the summary of an interaction effect between two different qualities (W and AR) and two different quantities (1.0% and 0.1%) of recycled PET used in experimental concrete composites. Statistical data, such as individual group means and standard deviations, derived from the statistical treatment of the series of ASTM compressive strength tests are presented here.

The two-way analysis of variance on the compressive strength (S) examined this most important engineering property in Table 14. In this tabulated analysis, the PET quality ("washed" and "as received") and PET quantity (0.1% and 1.0% PET content) relationship was a main concern. The close examination of the two attached bar charts is offering at the .05 level the following results.

The first bar chart of Table 14 concerned with PET quality responses during this ASTM test, revealed considerable mean difference between the "as received" groups mean (1946 PSI) and "washed" groups mean (2471 PSI). The reported mean difference (525 PSI) was about one and one-half of the total standard deviation (363.1 PSI) in its size at the 95% confidence level, which is statistically significant, F (1,16) = 36.75, p < .01. Therefore, null hypothesis 1 was rejected and research hypothesis 1 was supported.

The quantity bar chart of Table 14 is presenting a contrasting view. This graph displayed at the 95% confidence level that there was an overlap of the two specified quantities, where 1.0% PET content had group means of 2283 PSI and, 0.1% PET content groups recorded their mean 2134 PSI. The calculated 149 means' difference is less than one-half of the total standard deviation (363.1 PSI) at the 95% confidence level and therefore, is not statistically significant, F (1,16) = 2.95, p > .05. Therefore, the null hypothesis 2 was not rejected and research hypothesis 2 was not supported.

In Table 13 and Table 14, the interaction between all experimental concrete groups, as they have been affected by their distinct quality and quantity responses under the ASTM compressive strength (S) test conditions, was investigated. Table 13 and Table 14 is providing calculated data, means and standard deviations, for statistical treatment required by the adopted comparative research procedures.

Interpretation of the role of quality in Table 13 and Table 14 indicated that the level of quality was important in the compressive strength test measured performance.

Table 11

Recorded Maximum Loads and Calculated Compressive Strength (S) Values

	Compressive strength tests					
Composite group	1	2	3	4	5	*M*
Control						
Load (lbs.)	14200	14500	14400	15600	15400	-
S (PSI)	2009	2051	2037	2207	2179	2096.6
AR1						
Load	13300	13300	13900	13600	12200	-
S	1882	1882	1966	1924	1726	1876.0
AR.1						
Load	13200	14500	14550	15500	13500	-
S	1876	2051	2058	2193	1910	2015.8
W1						
Load	21300	16100	18750	19400	19500	-
S	3013	2278	2653	2745	2759	2689.6
W.1						
Load	18400	15300	14300	16700	14900	-
S	2603	2165	2023	2363	2108	2252.4

Note. Load values provided here are maximum applied loads carried by the concrete specimens during the test.

Table 12

Organization of the Compressive Strength (S) Test Data for Statistical Treatment as Required by the Computer Software Used

Row seq	Concrete type	PET qual	PET qty	Sample seq	*S* (PSI)	Composite group
1	1	0	0	1	2009	1
2	1	0	0	2	2051	1
3	1	0	0	3	2037	1
4	1	0	0	4	2207	1
5	1	0	0	5	2179	1
6	2	1	1	1	1882	2
7	2	1	1	2	1882	2
8	2	1	1	3	1966	2
9	2	1	1	4	1924	2
10	2	1	1	5	1726	2
11	2	1	2	1	1867	3
12	2	1	2	2	2051	3
13	2	1	2	3	2058	3
14	2	1	2	4	2193	3
15	2	1	2	5	1910	3
16	2	2	1	1	3013	4
17	2	2	1	2	2278	4
18	2	2	1	3	2653	4
19	2	2	1	4	2745	4
20	2	2	1	5	2759	4
21	2	2	2	1	2603	5
22	2	2	2	2	2165	5
23	2	2	2	3	2023	5
24	2	2	2	4	2363	5
25	2	2	2	5	2108	5

Note. See p. 50 for the detailed interpretation of the assigned numbers/values in this organization matrix.

Table 13

Compressive Strength (S) as Affected by the PET Quality and Quantity Interaction

	PET quantity		
PET quality	0.1%	1.0%	All groups
AR groups			
n	5	5	10
M (PSI)	2015.8	1876.0	1945.9
SD (PSI)	130.1	90.8	128.9
W groups			
n	5	5	10
M	2252.4	2689.6	2471.0
SD	232.5	266.1	329.5
All groups			
n	10	10	20
M	2134.1	2282.8	2208.4
SD	217.0	468.0	363.1

Note. n = experimental groups sample size

M = experimental groups mean

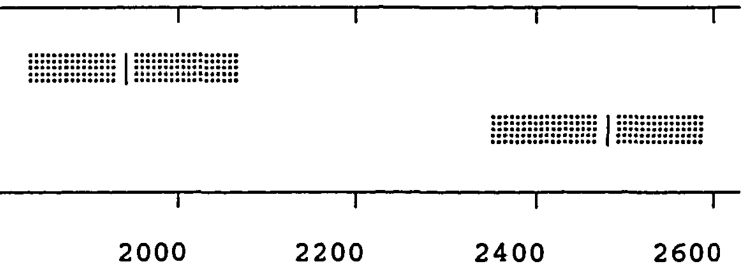
SD = sample standard deviation.

Table 14

Two-Way Analysis of Variance on Compressive Strength (S)

Source of variation	df	SS	MS	F	p
PET quality	1	1378650	1378650	36.75	< .01
PET quantity	1	110558	110558	2.95	> .05
Interaction	1	416161	416161	11.09	< .01
Within groups	16	600225	37514		
Total	19	2505595			

PET quality	M	Individual 95% confidence interval
ALL AR groups	1946	
All W groups	2471	



PET quantity	M	Individual 95% confidence interval
All 1.0% gps.	2283	
All 0.1% gps.	2134	

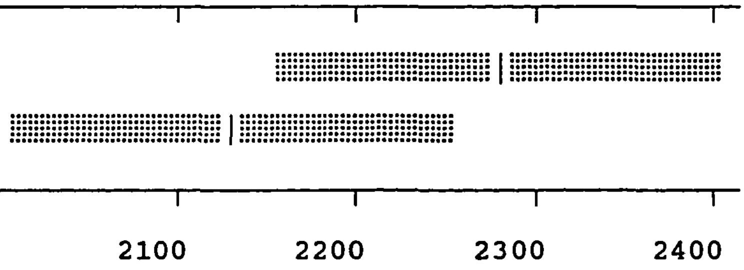
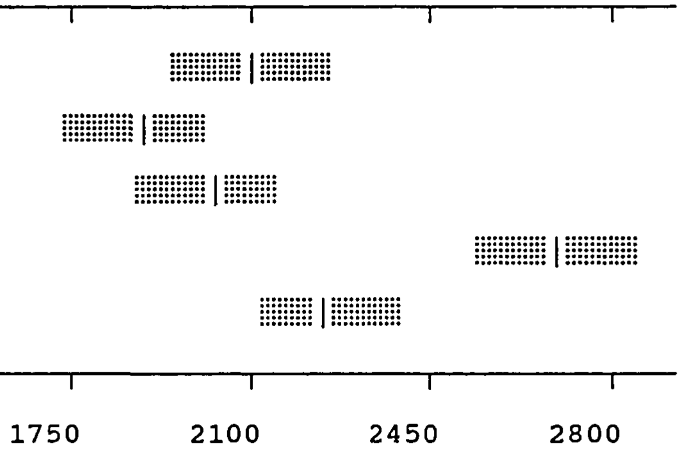


Table 15

Statistical Analysis of Variance on Compressive Strength (S)

Group	M	SD	Individual 95% confidence interval for mean based on pooled SD = 177.80
C	2096.6	89.8	
AR1	1876.0	90.8	
AR.1	2015.8	130.1	
W1	2689.6	266.1	
W.1	2252.4	232.5	



Source of variation	df	SS	MS	F	p
Between gps.	4	1955412	488853	15.46	< .0005
Within gps.	20	632508	31625		
Total	24	2587920			

Note. Sample size (n) for all tested concrete groups was 5.

Actually, the two best performances were accomplished by the "washed" PET groups. The highest test result was registered by the W1 experimental group (mean 2689.6 PSI) followed by the W.1 specimens with the group mean 2252.4 PSI. The third and fourth places were taken by the results of the AR.1 group (mean 2015.8 PSI) and the AR1 group with a mean of 1876.0 PSI respectively. This interaction was statistically significant, F (1.16) = p < .01.

A display of F-test and analysis of variance on compressive strength (S) is an integral part of Table 15. Inquiry into the distribution of the compressive strength means and standard deviations for all five studied concrete groups (including the control group) was needed to detect the statistical differences between the tested groups. Although null hypothesis 4 was rejected F (4,20) = 15.46, p < .0005, the equality of all means was rejected. The bar graph shows that the control group was not lower than the others. Therefore, research hypothesis 4 was not supported.

Research Question and Hypotheses Testing

Each of the four research questions, supported by a hypothesis, was respectively studied. The focus of this research was to answer these questions and also, to accept or reject their associated hypotheses through the statistical analysis of the performed laboratory tests. Specifically, results obtained from the conducted ASTM flexural, splitting tensile, and compressive strengths tests were used.

To respond appropriately to the research questions 1, 2, and 3, the data presented in Table 3, Table 8, and Table 13 were developed for evaluation of the performance of the three investigated ASTM tests. Therefore, a set of three graphs (see Figure 8, Figure 9, and Figure 10) was prepared to display the relationships (distributions and comparisons) crucial for answers to inquiring research questions and hypotheses.

Research Question and Hypothesis 1

Research question 1 answer. Is there a difference between the performance of "as received" and "washed" recycled PET aggregates (effect of PET quality) when used in experimental concrete composites as measured in terms of three ASTM test methods; flexural, splitting tensile, and compressive strengths tests?

To accurately answer the following research questions, it should be emphasized that two primary sources of data were needed for each test analysis. First, the tabulated means and standard deviations were analyzed for each investigated engineering property (flexural, splitting tensile, and compressive strengths) as was affected by the PET quality content. For these important values, Table 3, Table 8, and Table 13 were referenced. Second, the corresponding Figure 8, Figure 9, and Figure 10 became contributory in the interpretation of these statistical values as they have been organized in the graphs for each respective ASTM test.

Answer to the flexural strength research question. The statistical analysis of the flexural strength test results, consisted of groups means and sample standard deviations as presented in Table 3, offered the following outcome. The flexural strength R when compared statistically among all experimental groups which utilized the "as received" PET quality aggregate (n = 10) revealed M = 634.60 with SD =

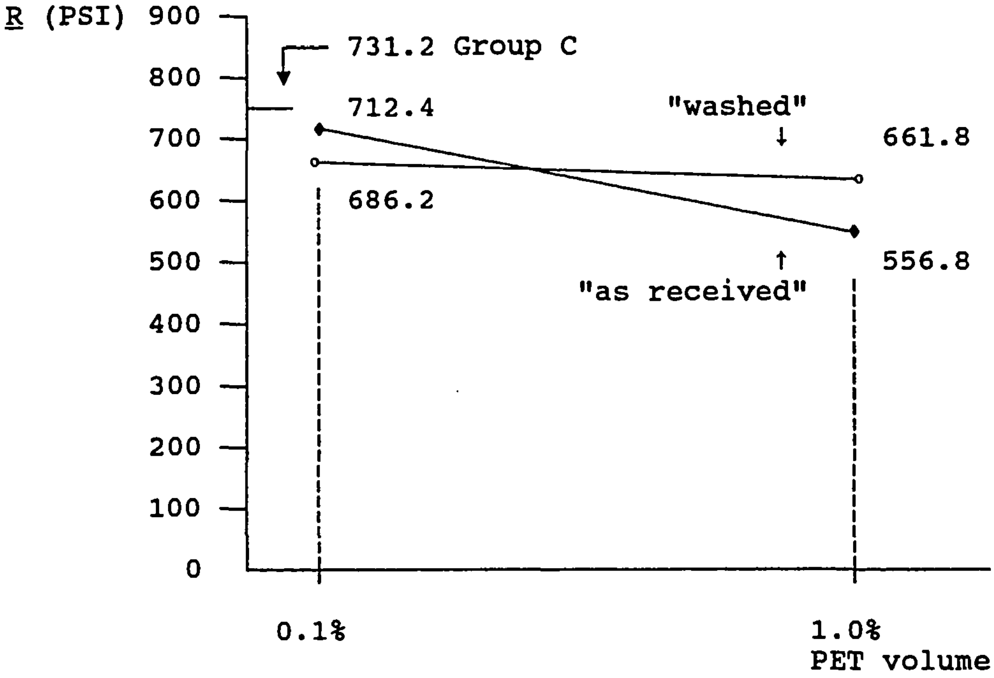


Figure 8. Comparison of the flexural strength (R) performance of concrete composite specimens utilizing "washed" and "as received" quality PET aggregates.

97.34 against the "washed" PET quality aggregate (n = 10) with M = 674.00 and SD = 47.74 in their respective concrete composite specimens.

Figure 8 indicates that there is no difference in between the performance of "as received" and "washed" recycled PET aggregates when used in experimental concrete composites. This judgement is based on the interpretation of the close proximity of the two observed graph lines and their intersection in the figure's middle region. The interaction effect was statistically significant indicating a slight tendency for "washed" concrete composite specimens to be more effective with 1.0% than with 0.1% PET content.

Answer to the splitting tensile strength research question. The splitting tensile strength (T) performance values, as they have been compiled in Table 8, presented means and standard deviations. Figure 9 is using these values and offers graphic interaction of this particular ASTM test performance where all experimental type concrete mix, "as received" and "washed" quality composition, are examined.

In Figure 9, the constructed graphs intersected each other in the large central region. This intersection implies that the differences are not, generally, of meaningful contributions; in this case, the performance of the investigated quality of "as received" and "washed" recycled PET aggregates when used in concrete experimental composites. However, the interaction effect was statistically significant since there is a slight inclination for "washed" composites to be more effective with 1.0% PET than with 0.1% PET aggregates.

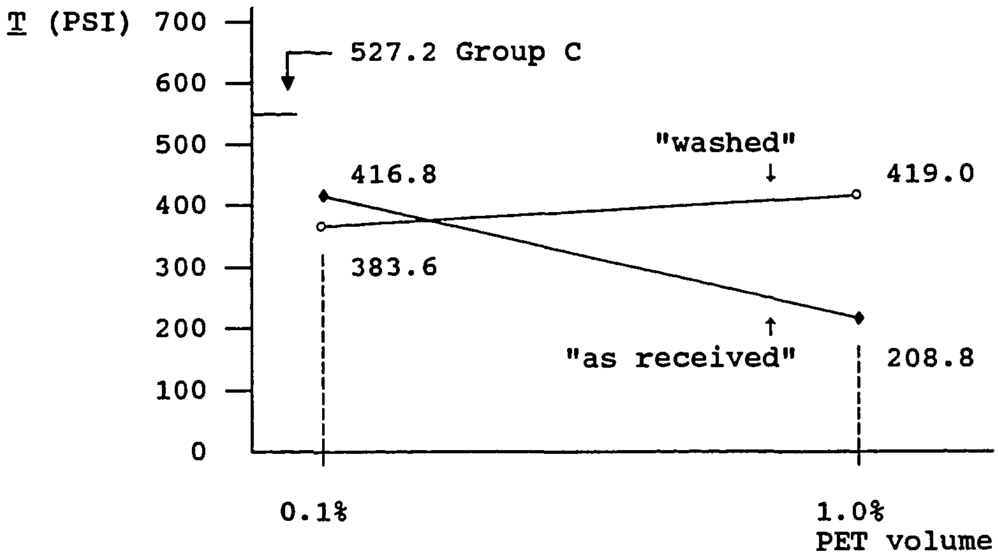


Figure 9. Comparison of the splitting tensile strength (T) performance of concrete composite specimens utilizing "washed" and "as received" quality PET aggregates.

Answer to the compressive strength research question. The compressive strength (S) means and standard deviations of all the involved experimental concrete groups, after they have been affected by the various PET quality, is carried by Table 13. Figure 10 is concerned with the implementation and expression of these same values in a graphic form.

Hence, Figure 10 is offering a very different view than the two prior ASTM test inquiries presented in Figure 8 and Figure 9. In this investigation, there is no evidence of the intersection among the two plotted graphs, because the performance of the "washed" PET composites delivered overall better test results (W.1 group M = 2252.4 and W1 group M = 2689.6) over the "as received" samples (AR.1 group M = 2015.8 and AR1 group M = 1876.0). The interaction effect was statistically significant, it revealed a clear tendency for "washed" composite specimens to be more effective with 1.0% than for 0.1% PET aggregates.

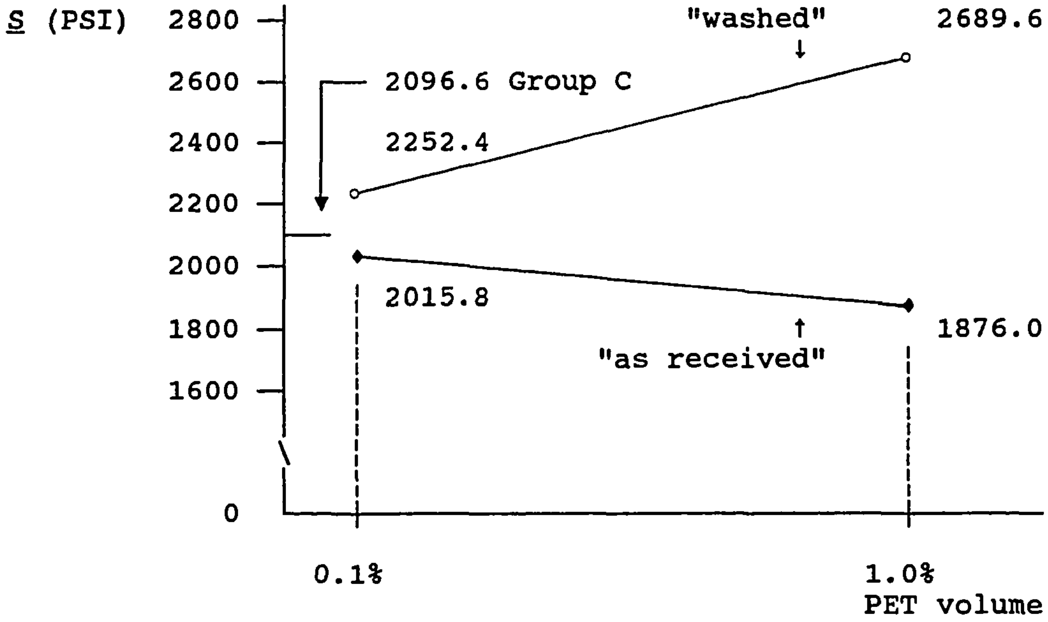


Figure 10. Comparison of the compressive strength (S) performance of concrete composite specimens utilizing "washed" and "as received" quality PET aggregates.

It can be concluded, that there is a difference between the performance of AR and W recycled PET aggregates when used in experimental concrete composites as was measured in terms of the ASTM compressive test. The "washed" PET quality outcome was superior to "as received" PET aggregates used.

Research hypothesis 1 testing. It was hypothesized that "washed" PET will perform better than "as received" recycled PET quality when used as aggregates in experimental concrete composites and measured in terms of three ASTM test methods; flexural, splitting tensile, and compressive strengths tests.

It should be pointed out that the two-way analysis of variance statistical treatment (Table 3, Table 4, Table 8, Table 9, Table 13, and Table 14) was employed here to decide to accept or reject this hypothesis. The research hypothesis has three parts, each part is concerned with the specific ASTM test results and, therefore, has to be tested separately.

Flexural strength hypothesis. The statistical treatment (Table 3 and Table 4) disclosed that the difference in mean flexural strength (R) between the "as received" and "washed" recycled PET quality, when used as aggregates in experimental concrete composite groups, was not statistically significant, F (1,16) = 2.84, $p > .05$. Therefore, based on the conclusion of the stated statistical analysis, null hypothesis 1 was not rejected (H_0: $\mu_{AR} = \mu_W$) and research hypothesis 1 was not supported.

Splitting tensile strength hypothesis. The mean splitting tensile strength (T), as analyzed in Table 8 and Table 9, unveiled the significant difference between the "as received" and "washed" recycled PET quality when applied as aggregates in experimental concrete composite specimens, F (1,16) = 61.77, $p < .01$, because the "washed" PET composite concrete performed better. On this statistical basis, null hypothesis 1 (H_0: $\mu_{AR} = \mu_W$) was rejected and research hypothesis 1 was supported.

Compressive strength hypothesis. By analyzing Table 13 and Table 14, the compressive strength (S) means revealed that there was a significant difference among the performance of the studied "as received" and "washed" group samples, F (1,16) = 36.75, $p < .01$. The concrete composites containing "washed" PET aggregates delivered better test performance and, based on the statistical analysis, null hypothesis 1 (H_0: $\mu_{AR} = \mu_W$) was rejected and research hypothesis 1 was supported.

Research Question and Hypothesis 2

Research question 2 answer. Is there a difference between the performance of 1.0% and 0.1% volume recycled PET aggregates (effect of PET quantity) when used in experimental concrete composites as measured in terms of three ASTM test methods; flexural, splitting tensile, and compressive strengths tests?

In general, two sources of statistical data were necessary for each research question answer. The tabulated means and standard deviation results, as they have been affected by PET quantity, were used in this particular investigated engineering test (Table 3, Table 4, Table 8, Table 8, Table 13, and Table 14). Also, the offspring graphs presented in Figure 8, Figure 9, and Figure 10 were taken into account during the interpretation of statistically treated values to answer the following set of research questions.

Answer to the flexural strength research question. The statistical summary of the flexural strength (R) laboratory test results, including group means and standard deviations, was presented in Table 3. In addition, the flexural strength values plotted into the graph of Figure 8 were necessary to answer this research question.

A close review of the data contained in Table 3, Table 4, and Figure 8, disclosed that all experimental groups with 0.1% content of PET performed better than any 1.0% PET content concrete composite groups. In other words, the lowest calculated mean of the flexural strength for 0.1% group was 686.2 (W.1 group) in comparison to the highest available mean of 661.8 for the group with 1.0% PET (W1 group).

Answer to the splitting tensile strength research question. The splitting tensile strength (T) means were assembled in Table 8 and Table 9 and then graphically presented in Figure 9. In practical terms, if the total means of 0.1% and 1.0% of PET groups are used for comparison purposes the following answer can be extrapolated.

The total splitting tensile strength mean for the 0.1% PET grouping was calculated to be 400.20. In contrast, the equivalent property of the observed 1.0% PET grouping was only 313.90. The difference between these two groups is slightly smaller than one total standard deviation (SD = 91.94). As a group, the 0.1% PET aggregates performed better in terms of the ASTM splitting tensile strength test.

Answer to the compressive strength research question. The observed engineering property results, compressive strength (S), means and standard deviations were assembled in Table 13 and Table 14. The concerned quantity relationship, 0.1% and 1.0% PET content, is a part not only of this tabulation but, also the graphical confirmation in Figure 10.

Since there is no clear pattern in the means distribution to trace easily the effect of the PET quantity on the performance of the experimental concrete composite specimens, the comparison of each group total mean was the most suitable way to evaluate this particular relationship and the associated research question. The 10 specimens of

1.0% group had a calculated total mean of 2282.8 which is about one-half of the total standard deviation (SD = 363.1) higher than the compared group of 0.1% with a total mean of 2134.1. Therefore, it can be answered that there is no meaningful difference between these two quantity groups even though the 1.0% PET group has a slightly higher group total mean.

Research hypothesis 2 testing. It was hypothesized that 1.0% volume PET will perform better than 0.1% volume recycled PET quantity when used as aggregates in an experimental concrete composites and measured in terms of three ASTM test methods; flexural, splitting tensile, and compressive strengths tests.

The two-way analysis of variance statistical technique was applied here to decide when to accept or reject this hypothesis. The research hypothesis has three parts, each part is concerned with the specific ASTM test results and, therefore, has to be tested separately.

Flexural strength hypothesis. The analysis in Table 3 and Table 4 acknowledged that the difference in mean flexural strength (R) between the 0.1% and 1.0% recycled PET quantity, when used as aggregates in experimental concrete composite specimens, was statistically significant, F (1,16) = 14.80, $p < .01$. The 0.1% PET quantity samples delivered better performance. Hence, based on the results of the cited statistical statement, null hypothesis 2 (H_0: $\mu_1 = \mu_{.1}$) was rejected but research hypothesis 2 was contradicted in direction.

Splitting tensile strength hypothesis. The mean distribution of the splitting tensile strength (T) was analyzed in Table 8 and Table 9. The results showed a statistical significant difference between the 0.1% and 1.0% recycled PET quantity when applied as aggregates in experimental concrete composite specimens, F (1,16) = 58.74, $p < .01$, because the 0.1% PET quantity in concrete composites performed much better. On this statistical basis, null hypothesis 2 was rejected (H_0: $\mu_1 = \mu_{.1}$) but research hypothesis 2 was contradicted in direction.

Compressive strength hypothesis. By investigating Table 14, the compressive strength (S) means distribution disclosed that there was no significant difference among the performance of the observed 0.1% and 1.0% group testing specimens, F (1,16) = 2.95, $p > .05$. Both 0.1% and 1.0% PET quantity concrete composites delivered similar test performance and, as a result, the statistical treatment affirmed the decision that null hypothesis 2 (H_0: $\mu_1 = \mu_{.1}$) was not rejected and research hypothesis 2 was not supported.

Research Question and Hypothesis 3

Research question 3 answer. Is there an interaction between the quality and quantity of recycled PET aggregates when used in experimental concrete composites as measured in terms of three ASTM test methods; flexural, splitting tensile, and compressive strengths tests?

For the most part, two main statistical data were needed to answer this research question. The tables of means and standard deviations as they have been affected by the PET quality and quantity interaction during individually performed ASTM tests (Table 3, Table 4, Table 8, Table 9, Table 13, and Table 14) were therefore utilized.

The second input of vital data arrived from the corresponding graphs, which are based on the results of the mentioned tables, and are presented in Figure 8, Figure 9, and Figure 10. All this information contributed to answer the next set of research questions.

Answer to flexural strength research question. The statistical results of the laboratory test on the flexural strength (R), containing group means and standard deviations, were presented in Table 3 and Table 4. In addition, the flexural strength test values plotted into the graph of Figure 8 were examined prior to answering this research question.

The study of the two described statistical records from Table 3, Table 4, and Figure 8 indicated that when the "as quantity, 0.1% and 1.0%, were expressed by the graph (Figure 8), there was a significant interaction (Table 4) between the quality and quantity of recycled PET aggregates in the experimental concrete composites. This occurrence is supported by the evident intersection of these two representative graph lines.

Answer to splitting tensile strength research question. The overview of the statistical treatment summary concerned about splitting tensile strength (T) behavior was assembled in Table 8 and Table 9 and, also graphically in Figure 9. The purpose of Figure 9 was to show all involved group means, as they have been organized by the quality (AR and W groups) and selected quantity with 0.1% and 1.0% PET contents. These tables and this figure show significant interaction of the quality and quantity of PET aggregates using the described investigated concrete composite specimens during their ASTM splitting tensile strength testing. This research answer is shown by the actual intersection of the two representative graphs in their middle region.

Answer to compressive strength research question. This calculated engineering property, with its calculated group means and standard deviations, was organized in Table 13 and Table 14. The interaction of the compressive strength (S) values among the selected quality (AR and W groups) and quantity (0.1% and 1.0% PET contents) was then exhibited in Figure 10.

In this particular test setting there is no recorded intersection of the two plotted graphs, where each graph is representing described effects of the quality and quantity of recycled PET aggregates in experimental concrete composite groups. So, it can be answered that there was no interaction between quality and quantity of PET aggregates in concrete composites during the compressive strength testing.

Research hypothesis 3 testing. It was hypothesized that the difference between the performance of 0.1% and 1.0% volume recycled PET content in the experimental groups (effect of PET quantity) will be larger in "washed" than "as received" recycled PET quality when used as aggregates in concrete composites and measured in terms of three ASTM test methods; flexural, splitting tensile, and compressive strength tests.

Statistically, the two-way analysis of variance method was selected here to determine when to accept or reject this hypothesis. The research hypothesis has three parts, each part is referring to the specific ASTM test and, hence, has to be tested separately.

Flexural strength hypothesis. The inquiry into Table 4, where two-way analysis of variance on flexural strength (*R*) was exhibited, was essential. Furthermore, Table 3 together with Figure 8, provided all necessary group means and standard deviations for flexural strength as was affected by the PET quality and quantity interaction.

The test's statistical analysis for this engineering property disclosed that the difference between the performance of 0.1% and 1.0% PET content was not larger in "washed" as was originally hypothesized, but was actually larger in the "as received" recycled PET quality setting when used as aggregates in concrete composite specimens. Based on the acquired data, the interaction was significant, F (1,16) = 7.86, p < .05, and as a result, null hypothesis 3 was rejected H_0: $(\mu_{W1} - \mu_{W.1}) = (\mu_{AR1} - \mu_{AR.1})$ but research hypothesis 3 was contradicted in direction.

Splitting tensile strength hypothesis. Table 8, Table 9, and Figure 9 provided the statistical framework necessary to test this hypothesis. The investigation of splitting tensile strength (T) indicated that there existed a difference between the performance of 0.1% and 1.0% PET content when "washed" and "as received" recycled PET was used as aggregates in experimental concrete composites.

It was evident that the tested "as received" groups had a larger mean difference than the "washed" groups as the initial hypothesis proposed. On the basis of the statistical analysis, the interaction was significant, F (1,16) = 116.80, p < .01, therefore, null hypothesis 3 was rejected H_0: $(\mu_{W1} - \mu_{W.1}) = (\mu_{AR1} - \mu_{AR.1})$ but research hypothesis 3 was contradicted in direction (note that the "washed" line in Figure 9 has a smaller slope than the "as received" line.

Compressive strength hypothesis. Interpretation of the data as offered by Table 13, Table 14, and Figure 10 was essential when the hypothesis was tested. The analysis of the compressive strength (S) property confirmed the validity of the research hypothesis since it predicted a difference between the performance of 0.1% and 1.0% recycled PET content in the experimental groups with the "washed" PET having a larger effect of PET quantity than was experienced by the "as received" PET groups. It was confirmed that the outlined difference was statistically significant, $F(1,16) = 11.09$, $p < .01$, and therefore, null hypothesis 3 was rejected H_0: $(\mu_{W1} - \mu_{W.1}) = (\mu_{AR1} - \mu_{AR.1})$ and research hypothesis 3 was supported (note that the "washed" line in Figure 10 has a larger slope than the "as received" line).

Research Question and Hypothesis 4

Research question 4 answer. Is there a difference in performance between the plain concrete (control group) and four experimental groups of the PET reinforced concrete composites as measured in terms of three ASTM test methods; flexural, splitting tensile, and compressive strengths tests?

Two main sources of information were instrumental in answering the set of three research questions. The means and standard deviations of Table 5, Table 10, and Table 15 offered an inside look into the test performance on the studied engineering properties. The statistical data were also supported by the corresponding Figure 8, Figure 9, and Figure 10, especially by their graphs displaying the relations between the four experimental groups (AR1, AR.1, W1, and W.1). The role of the control group (C) was to serve to all other composite groups in the graph as a point of reference during the investigation process.

Answer to flexural strength research question. The statistical data on the flexural strength ($\underline{R}$) property, as assembled in Table 5 and graphically displayed in Figure 8, were needed to answer this research question. According to these test records, there was a noticeable difference in performance between the plain concrete (control group C) and the rest of the four tested experimental groups of the PET reinforced concrete composites.

The control group (C) with calculated mean distribution 731.2 and standard deviation 68.77 outperformed all PET concrete composite groups. Review of the test results indicated that the nearest experimental group AR.1 ("as received" with 0.1% PET content) pulled calculated group mean 712.4 and standard deviation 62.74. The lowest calculated performance was recorded by AR1 specimens with group mean 556.8 and standard deviation 47.47.

Answer to splitting tensile strength research question. Table 10 and Figure 9 offered the necessary statistical data essential to answering this research question. The calculated test splitting tensile strength (T) property results furnished evidence that the plain concrete specimens (control group C) scored better than all four experimental groups of the PET reinforced concrete composites as was measured and compared using group means.

The control group (C) examined mean 527.2 (standard deviation 43.75) was greater than any of the experimental PET groups. For a comparison, the second highest performance during the testing of this engineering property was recorded by the W1 group, ("washed" with 1% PET content) with a mean of 419.0 and standard deviation of 24.97. The lowest reading appeared in the AR1 group with a mean of 208.8 and a standard deviation of 27.48.

Answer to compressive strength research question. The collected and calculated data on the compressive strength (S) engineering property were statistically treated and organized into Table 15 and Figure 10. Based on these records, the control group (C) performance was slightly lower than the mean of 2096.6 and a standard deviation of 89.8. In this most important ASTM concrete criterion, the compressive strength test, the control group was outperformed by both "washed" PET quality experimental groups. First by W1 group with a mean of 2689.6 and a standard deviation of 266.1, and also by the second "washed" group (W.1) with a mean of 2252.4 and standard deviation of 232.5.

In contrast, the control group specimens presented higher group mean than "as received" PET quality reinforced concrete composite groups. The experimental group AR.1 displayed a mean of 2015.8 and standard deviation of 130.1, the lowest test readings were recorded by AR1 group, mean 1876.0 and standard deviation 90.8.

Research hypothesis 4 testing. It was hypothesized that each experimental group of the PET reinforced concrete composites will be superior to plain concrete (control group) as measured in terms of three ASTM test methods; flexural, splitting tensile, and compressive strengths tests.

Hypothesis 4 was tested with the "Dunnett Method of Multiple Comparisons" (Glass & Hopkins, 1984). This particular method can be described as tailor-made for the situations where it is required to compare each of the J-1 means with one predesignated mean, i.e., mean of the control concrete group in the case of this research.

Thus, with the Dunnett MC method there are C = J-1 planned pairwise contrasts, where each contrast is against the mean of the predesignated control group (M_c). The described statistical relationships can be written into the following equation, $t = M_j - M_c / \sqrt{MS_c(1/n_j + 1/n_c)}$.

Where: t = critical value 2.65, obtained from Glass and Hopkins (1984), Table M, p. 555

M_c = control group mean

M_j = experimental group mean

MS_c = means square error

n_c = control group size

n_j = experimental group size

This research hypothesis has three parts, each part is concerned with the specific ASTM test and also, with the four experimental groups performance against the control group consisting of plain concrete. Hence, there were four separate Dunnett MC method calculations prepared for AR1, AR.1, W1, and W.1 group within each type of test conducted. Table 16 carried calculated comparison values for the flexural strength test, Table 17 for the splitting tensile strength test, and Table 18 for the compressive strength test. All pertinent statistical data arrived from the respective test tables, such as Table 5, Table 10, and Table 15.

Flexural strength hypothesis. Based on the interpretation of the statistical results furnished by Table 5 and Table 16, the following was evident. AR.1, W1, and

W.1 experimental groups of PET reinforced concrete composites were not significantly different than calculated "critical value" of 93.842. Therefore, these three parts of null hypothesis 4 were not rejected (H_0: $\mu_c = \mu_{AR.1} = \mu_{W.1} = \mu_{W1}$) and research hypothesis 4 which predicted that the experimental groups would be superior to plain concrete

Table 16

Flexural Strength (R) Test Values of PET Concrete Composites in Comparison to Control Group

Composite group	$M_j - M_c = A$	p (compared to A)
AR1	556.8-731.2 = |174.4|	< .05
AR.1	712.4-731.2 = |18.8|	> .05
W1	661.8-731.2 = |69.4|	> .05
W.1	686.2-731.2 = |45.0|	> .05

Note. The following necessary values remained constant during Dunnett MC statistical analysis: $n_C = 5$, $n_j = 5$, $(1/n_j - 1/n_c) = .4$, $MS_c = 3135$ (obtained from Table 3), $df = 20$ (df associated with MS_c), α (alpha) = .05, J = 5 (number of means, including control), critical t-value = 2.65, and calculated "critical value" $93.842 = t\sqrt{3135(.4)}$.

(control group), as measured in terms of the ASTM flexural strength (R) test, was not supported.

AR1 experimental group of PET reinforced concrete composite's (1.0% "as received" PET content) lower test results indicated an A-value of 174.4, which is larger than the calculated "critical value" of 93.842. Also, it is the only value in flexural strength tests which is significant at the .05 level, therefore, this part of null hypothesis 4 was rejected (H_0: $\mu_C = \mu_{AR1}$) but research hypothesis 4 was contradicted.

Splitting tensile strength hypothesis. By analyzing Table 10 and the Dunnett statistic for comparing treatment means with a control group (Table 17), it was recognized that all four tested experimental PET concrete composite groups achieved significantly lower total group means and consequently ended up with larger A-values than was the calculated "critical value" of 50.000 for splitting tensile strength (T).

The experimental group AR1 disclosed A-value of 318.4, group AR.1 had 110.4, group W1 had 108.2, and group W.1 displayed A-value of 143.6; all values were significant at the .05 level. The statistical treatment confirmed the decision to reject null hypothesis 4 (H_0: $\mu_C = \mu_{AR.1} = \mu_{W.1} = \mu_{AR1} = \mu_{W1}$) but it contradicted research hypothesis 4 in direction.

Table 17

Splitting Tensile Strength (T) Test Values of PET Concrete Composites in Comparison to Control Group

Composite group	$M_j - M_c = A$	p (compared to A)
AR1	208.8-527.2 = |318.4|	< .05
AR.1	416.8-527.2 = |110.4|	< .05
W1	419.0-527.2 = |108.2|	< .05
W.1	383.6-527.2 = |143.6|	< .05

Note. The following necessary values remained constant during Dunnett MC statistical analysis: $n_C = 5$, $n_j = 5$, $(1/n_j - 1/n_c) = .4$, $MS_c = 890$ (obtained from Table 8), $df = 20$ (df associated with MS_c), α (alpha) = .05, J = 5 (number of means, including control), critical t-value = 2.65, and calculated "critical value" 50.000 = $t\sqrt{890(.4)}$.

Compressive strength hypothesis. The careful scrutiny of Table 15 which provided statistical analysis of variance on compressive strength (S), and Table 18 with Dunnett's multiple group comparison treatment technique, was essential not only to the initial statistical investigation but to the testing of this hypothesis as well.

First, only the AR.1 experimental PET composite group (0.1% "as received" PET content) was not significantly different with an A-value of value of 80.8, in comparison to the calculated "critical value" of 112.472. Since research hypothesis 4 suggested that the PET concrete composites would perform better than a control group consisting of

Table 18

Compressive Strength (S) Test Values of PET Concrete Composites in Comparison to Control Group

Composite group	$M_j - M_c = A$	p (compared to A)
AR1	1876.0-2096.6 = |220.6|	$< .05$
AR.1	2015.8-2096.6 = |80.8|	$> .05$
W1	2689.6-2096.6 = |593.0|	$< .05$
W.1	2252.4-2096.6 = |155.8|	$< .05$

Note. The following necessary values remained constant during Dunnett MC statistical analysis: $n_C = 5$, $n_j = 5$, $(1/n_j - 1/n_c) = .4$, $MS_c = 31625$ (obtained from Table 13), $df = 20$ (df associated with MS_c), α (alpha) = .05, J = 5 (number of means, including control), critical t-value = 2.65, and calculated "critical value" $112.472 = \sqrt{31625(.4)}$.

plain concrete (as measured by the ASTM compressive strength test), it was not supported and this part of null hypothesis 4 was not rejected (H_0: $\mu_C = \mu_{AR.1}$).

Second, W1 and W.1 experimental groups of PET concrete composites reported an A-value of 593.0 and 155.8 respectively. Both values were larger than the calculated "critical value" of 112.472 which is significant at the .05 level. Hence, based on the presented statistical treatment, null hypothesis 4 was rejected (H_0: $\mu_C = \mu_{W.1} = \mu_{W1}$) and research hypothesis 4 concerned with W1 and W.1 composite groups was supported.

The third testing situation pertained to AR1 experimental concrete PET composite group. This particular group recorded the lowest total group mean of 1876.0 in comparison to the control group mean of 2096.6. The calculation acknowledged that an A-value of 220.6 was significantly larger than the calculated "critical value" of 112.472 at the .05 level. Therefore, null hypothesis 4 was rejected (H_0: $\mu_C = \mu_{AR1}$) but this part of research hypothesis 4 was contradicted in direction.

CHAPTER V

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Summary

The analysis of reinforced concrete composites utilizing recycled polyethylene terephthalate thermoplastic (PET), was the main aim of this research. The study's intention was to determine the unknown responses of concrete composites reinforced with PET aggregates after being cured for the required 28-day period and then subjected to non-reversed loading. Hence, in this investigation, the flexural, splitting tensile, and compressive strengths testing, as regulated by the ASTM Standards, were fully adopted and closely monitored throughout the entire experimental cycle of the project.

The foregoing parts of this dissertation were concerned with the review of literature for recent information and accumulated knowledge with respect to various concrete composites' properties and their applications. Attention was also given to inquiry into the contemporary PET thermoplastic recycling philosophies and available technologies as PET packaging is a billion pounds per year production, and will remain one of the largest sources of plastic wastes in the future.

Reduction in the quantity of solid waste through utilization of recycled PET material was seen as an unorthodox applied research undertaking leading to the partial solution of the growing ecological problems. This was why this research work focused on the investigation of PET reinforced role in concrete composites. In particular, this research project adopted the idea to analyze the specific size and volume of the polyethylene terephthalate thermoplastic aggregate. Such PET material, in the form of chips, is currently commercially available and, its origin can be traced directly to recycled soft drink beverage containers.

Pavements and floors of residential, industrial or public constructions, usually erected from type I portland cement concrete, were suggested as a prime target because of their technological suitability, combined with the extraordinary volume potential for future recycled PET reinforced concrete composites. Accordingly, the methodology of this research was designed to give answers as to how any of the experimental group formulations performed under the governing and generally accepted ASTM regulations.

A total of four experimental test groups were used with two different types of PET recycled aggregates, "washed" and "as received," with additional quantity divisions of PET aggregate in volume fractions of 0.1% and 1.0% respectively. Importantly, all recycled PET chips used as aggregates were randomly oriented in the plain concrete mix. Also, for comparison purposes, a control group consisting of the plain concrete without any PET aggregate was maintained.

If summarized, flexural, splitting tensile, and compressive strengths tests were conducted with each ASTM test carrying the identical number of five specimens (sample size). Each laboratory test composition make-up was organized as follows: control group, 0.1% "washed", 1.0% "washed," 0.1% "as received," and finally, 1.0% "as received" PET content group. The resultant 25 specimens were prepared for each conducted ASTM test, which provided a total of 75 specimens for the three test investigations.

It was believed that if the experimental PET concrete composite formulation would be allowed to be correctly proportioned and mixed, then the end product (concrete composite samples) would deliver a better test performance than the plain concrete of the control group. This belief was based on the principle that a reinforcing agent, such as PET aggregate, has to be exposed to the same strain and consequent deformation as the surrounding concrete mass in order to postpone the unwanted separation of the primary concrete composite materials under induced loads.

In practical terms, this can be interpreted that the mechanical properties of used PET would enhance the basic concrete in the direction of higher/favorable ASTM test readings. Moreover, the anticipated improvements, for instance, in the overall resistance to spalling, wearability, cavitation, or even reduction of brittleness of the experimental PET concrete composites, were expected.

Based on the previously documented concrete technology developments, it was believed that the cause/effect relationship of using the PET aggregates as a reinforcing agent in concrete composites could be decided in a laboratory environment through standardized specimen testing.

Conclusions

It should be emphasized that the problem of this research study was to analyze the flexural, splitting tensile, and compressive strengths of the various concrete composite formulations utilizing PET as a reinforcing material in the concrete matrix.

The conclusion statements of this research were primarily acquired from the results reported in Chapter IV, where the collected test data were compiled, sorted and statistically analyzed. Research questions and associated hypotheses were tested with two-way analysis of variance, with the exception of hypothesis 4 which was tested by the more suitable Dunnett MC statistic for comparing treatment means with a control group. Henceforth, the four research hypotheses were restated and complemented with a brief descriptive explanation of the findings and conclusions per the respective ASTM test performed.

Research Hypothesis 1 Findings/Conclusions

It was hypothesized that the "washed" PET will perform better than "as received" recycled PET quality when used as aggregates in experimental concrete composites and measured in terms of three ASTM test methods; flexural, splitting tensile, and compressive strength tests.

Flexural strength (R). It was found that the 39.40 PSI difference in mean flexural strength between the "washed" M = 674.00 and "as received" M = 634.60 (Table 3) recycled quality when used as aggregates in experimental concrete composite groups was not statistically significant. Therefore, null hypothesis 1 was not rejected and research hypothesis 1 was not supported.

Splitting tensile strength (T). It was found that the 88.50 PSI difference in mean splitting tensile strength between the "washed" M =401.30 and "as received" M = 312.80 (Table 8) recycled PET quality when used as aggregates in experimental concrete composite groups was statistically significant because, the "washed" PET quality performed better. Therefore, null hypothesis 1 was rejected and research hypothesis 1 was supported.

Compressive strength (S). It was found that there was a fairly large 525.10 PSI difference in mean compressive strength between the "washed" M = 2471.00 and "as received" M = 1945.90 (Table 13) recycled PET quality when used as aggregates in experimental concrete composite groups was statistically significant because of the superior "washed" PET quality performance. Therefore, null hypothesis 1 was rejected and research hypothesis 1 was supported.

<u>Conclusions</u>. The findings from the three ASTM laboratory test data analyses, as they have been tested by research hypothesis 1, were examined and the following conclusions may be reported:

* The "washed" PET performed better than "as received" recycled PET quality, when used as aggregates in concrete composites, in splitting tensile strength (<u>T</u>) and also, in compressive strength (<u>S</u>) tests. Specifically the "washed" PET content presence was accountable for 28.29% or 88.50 PSI higher performance in <u>T</u> property (Table 8) and, 26.98% or 525.10 PSI higher performance in <u>S</u> property (Table 13) over the "as received" recycled PET concrete composites.

* In flexural strength (<u>R</u>) testing, it was found that concrete composites with the "washed" content did not perform significantly better in comparison to the "as received" PET composites (see Table 3 and Table 4).

* In summary, the "washed" recycled PET content contributed positively toward the overall better performance in the experimental concrete composites over "as received" PET quality when measured in terms of <u>R</u>, <u>T</u>, and <u>S</u> strengths (ASTM tests). The superior position of "washed" over "as received" PET aggregates can be credited to the washing solvent technology which entirely removes the unwanted foreign contaminants from a polyethylene's surface such as sugar, adhesives, labels, and many other impurities found in recycled PET containers; hence, better surface bonding

between the PET chips and the cementicious matrix is achieved.

Research Hypothesis 2 Findings/Conclusions

It was hypothesized that 1.0% volume PET will perform better than 0.1% volume recycled PET quantity when used as aggregates in experimental concrete composites and measured in terms of three ASTM test methods; flexural, splitting tensile, and compressive strengths tests.

Flexural strength (R). It was found that the 90.00 PSI difference in mean flexural strength between the 0.1% ($\underline{M}$ = 699.30) and 1.0% ($\underline{M}$ = 609.30) recycled PET quantity when used as aggregates in experimental concrete composite groups was statistically significant, however, the 0.1% PET quantity performed better (Table 3 and Table 4). Therefore, null hypothesis 2 was rejected, however, research hypothesis 2 was contradicted in direction because the 0.1% was found to be superior to 1.0% PET quantity.

Splitting tensile strength (T). It was found that the 86.30 PSI difference in mean splitting tensile strength between the 0.1% ($\underline{M}$ = 400.20) and 1.0% ($\underline{M}$ = 313.90) recycled PET quantity when used as aggregates in experimental concrete composite groups was statistically significant, however, the 0.1% PET quantity performed better (Table 8 and Table 9). Therefore, null hypothesis 2 was rejected, however, research hypothesis 2 was contradicted in direction.

Compressive strength (S). It was found that the 148.70 PSI difference in mean compressive strength between the 0.1% (M = 2134.10) and 1.0% (M = 2282.80) recycled PET quantity when used as aggregates in experimental concrete composite groups was not statistically significant (Table 13 and Table 14). Therefore, null hypothesis 2 was not rejected and research hypothesis 2 was not supported.

Conclusions. The findings from the three ASTM laboratory test data analyses, as they have been tested by research hypothesis 2, were examined and the following conclusions may be stated:

* The 0.1% PET performed better overall than 1.0% recycled PET quantity, when used as aggregates in concrete composites, in flexural strength (R) and also, in splitting tensile strength (T) tests. Particularly, the 0.1% PET content presence was accountable for 14.77% or 90.00 PSI better performance in R property (Table 3) and 27.49% or 86.30 PSI higher performance in T property (Table 8) over the 1.0% recycled PET concrete composites.

* In compressive strength (S) testing, it was found that concrete composites with the 1.0% content of recycled PET delivered better overall S performance when compared to 0.1% PET composites test data. The existence of the 6.97% or 148.70 PSI difference (Table 13) was not statistically significant, therefore, the data did not support research hypothesis 2.

* In summary, the effect of quantity on the experimental PET concrete composites delivered mixed results when performance was measured in terms of the ASTM tests. Less PET quantity (0.1%) had positive impact on R and T properties, however, S property was more effective with 1.0% than with 0.1% of PET content.

Research Hypothesis 3 Findings/Conclusions

It was hypothesized that the difference between the performance of 0.1% and 1.0% volume recycled PET content in the experimental groups (effect of PET quantity) will be larger in "washed" than "as received" recycled PET quality when used as aggregates in concrete composites and measured in terms of three ASTM test methods; flexural, splitting tensile, and compressive strength tests.

Flexural strength (R). It was found that the difference in mean flexural strength between the performance of 0.1% and 1.0% PET content (Table 3) was not larger in "washed" (24.40 PSI) as was originally hypothesized, but was actually larger in the "as received" (155.60 PSI) recycled PET quality setting when used as aggregates in concrete composite specimens. The found presence of such differences was also statistically significant, therefore, null hypothesis 3 was rejected and research hypothesis 3 was contradicted in direction.

Splitting tensile strength (T). It was found that the tested "as received" groups had a larger mean difference

(208.00 PSI) than was experienced in the "washed" (35.40 PSI) experimental groups (Table 8 and Figure 9). This finding is just the opposite than what was suggested by the research hypothesis 3. Therefore, on the basis of statistical analysis, the difference was significant, and null hypothesis 3 was rejected and research hypothesis 3 was contradicted.

Compressive strength (S). It was found that the difference in mean compressive strength was statistically significant between the performance of 0.1% and 1.0% recycled PET content in the experimental groups (Table 13), with the "washed" PET having a larger effect of PET quantity (437.20 PSI) than was recorded by the "as received" PET concrete composite groups (139.80 PSI). The results in this test were in full accordance with the research hypothesis 3 prediction, therefore, null hypothesis 3 was rejected and research hypothesis 3 was supported.

Conclusions. The findings from the three preceding ASTM laboratory tests, as they have been tested by research hypothesis 3, were investigated and some conclusions emerged from their analyses:

* Based on the two ASTM test findings, flexural strength (R) and splitting tensile (T) tests, it can be reported that the difference between the performance of 0.1% and 1.0% recycled PET content in the experimental groups was larger in the "as received" PET concrete composites. In

"washed" composites tested, R property had a mean difference of 24.40 PSI which is 15.68% of "as received" with a 155.60 PSI difference (Table 3). A similar pattern was found in the tested T property where the mean difference was 35.40 PSI in "washed" composites, which represents 17.02% of the "as received" difference of 208.00 PSI (Table 8).

* In the compressive strength (S) property, testing diametrally differed from results acquired in R and T tests. The calculated mean difference of 139.80 PSI appeared in "as received" concrete composites which is 31.98% of the "washed" larger difference of 437.20 PSI (Table 13).

* To generalize in this situation is not possible because the mixed results did not demonstrate any trend, it is not credible to draw a final conclusion as to which type of PET quality concrete composites, "washed" or "as received," will deliver a larger difference between the performance of 0.1% and 1.0% recycled PET content. But, the larger mean difference in the S property testing tends to indicate that "washed" composites may have a larger difference, and therefore, this conclusion will be in accordance and supportive of research hypothesis 3.

Research Hypothesis 4 Findings/Conclusions

It was hypothesized that each experimental group of the PET reinforced concrete composites will be superior to plain concrete (control group) as measured in terms of three ASTM test methods; flexural, splitting tensile, and compressive strengths tests.

Flexural strength (R). It was found that the experimental PET group means, in comparison to the control group mean, did not perform better. Therefore, research hypothesis 4 was not supported.

Splitting tensile strength (T). It was found that the experimental PET group means, in comparison to the control group mean, did not performed better. Therefore, research hypothesis 4 was not supported.

Compressive strength (S). It was found that the experimental PET group means, in comparison to the control group mean, performed in the following way. Only the "washed" groups were superior to the control group, but "as received" groups were not superior to the control group. Therefore research hypothesis 4 was only partially supported.

Conclusions. The findings from the three ASTM laboratory test data analyses, as they have been tested by research hypothesis 4, were thoroughly examined. When summarized, the following conclusions could be drawn:

* In flexural strength (R) testing, research hypothesis 4 was not supported.

* In splitting tensile strength (T) testing, research hypothesis 4 was not supported.

* In compressive strength (S) testing, research hypothesis 4 was only partially supported since only the W1 and W.1 experimental groups were superior to the control group.

Recommendations

This research project has been directed towards a new approach to PET reuse. It is believed that a partial solution may be found in concrete, especially knowing that concrete remains only slightly exposed to the growing plastic presence. This study's outcomes revealed that the utilization of PET aggregate in concrete pavements is feasible since, specific PET quality ("washed" and "as received") and quantity (0.1% and 1.0%) positively responded to induced tests and their analyses.

Based on the findings of this study, it is recommended that the recycled PET concrete composites' development continue because there is a growing need for more laboratory and field test data before this concept can be confidently applied in a large scale industry-wide. Hence, additional investigation and research should concentrate on the following areas of interest.

1. Test and analyze the impact of larger amounts than 1.0% recycled PET volume aggregate on the concrete composites and their strength test performance.

2. Test and analyze the effects of commonly used admixtures on the workability of recycled PET concrete composites.

3. Test and analyze to what extent crystalline growth may be adequate to increase recycled PET concrete composites' strength. The scanning electron microscopy (SEM) technique may be utilized to investigate the microstructural features of the dehydrated concrete composites as well as the interface characteristics between the PET aggregates and primary concrete matrix.

4. Test and analyze the significance of the chemical treatment on the surface of recycled PET aggregate prior to mixing of PET concrete composites. The main endeavor should be the improvement of the bonding between the PET aggregate surface and the composites cementitious paste.

5. Test and analyze the role of recycled PET's limited reductions in strength after failure had occurred. The presence of PET aggregates may maintain the integrity of failed/fragmented concrete composite specimens as noted in this study. In actual construction situations, the PET reinforcements may exhibit necessary cohesiveness when catastrophic failure in the strength of the concrete composite structure is eminent.

6. Test and analyze a crack-stop mechanism for shrinkage stresses in recycled PET concrete composites. Investigate further the stresses which occur immediately

after the concrete begins to set, resulting in numerous microcracks which can, if connected, grow into a major crack unless introduced "barriers" (PET chips/aggregates) prevent the concrete from evolving into such an unwanted situation.

7. Test and analyze the quasi-ductile property of the recycled PET concrete composites. Investigate further this new and unusual engineering property caused by the mixing of ductile PET chips into an inherently brittle concrete matrix.

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