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Recycling and reuse of reclaimed portland cement concrete aggregate

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Recycling and Reuse of Reclaimed Portland Cement Concrete Aggregate

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RECYCLING AND REUSE OF RECLAIMED PORTLAND CEMENT CONCRETE AGGREGATE

BY

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ABSTRACT

The substitution of natural aggregate with reclaimed Portland cement concrete (RPCC) could be a convenient solution to satisfy the growing requirement of aggregate.

The purpose of this research was to study the behavior of RPCC aggregates in Portland cement concrete and embankment. For the first case, several batches of concrete were prepared with RPCC aggregate, natural aggregate, different water cement ratio (WCR) and different maximum size of the aggregate. Standard tests were performed on RPCC and natural aggregates, concrete made with recycled and natural aggregate, including specific gravity and absorption, slump and compression tests. For the second case, shear tests were performed on RPCC aggregate to obtain the failure envelope and the friction angle.

The lower specific gravity and higher absorption of RPCC aggregate influence the parameters of the concrete batches and the final cost of concrete. Monitoring the properties of the recycled material is strongly recommended to achieve a well designed concrete.

From the slump tests, for a given WCR, concrete made from RPCC aggregate shows a higher slump, level of workability and plasticity than a conventional concrete. f'c versus age results suggest that as time increases, f'c from concrete made with recycled aggregate gets closer and have a comparable value to that of conventional.

From f'c versus WCR curves, an equivalent WCR for concrete made from RPCC aggregate to achieve the same f'c can be determined. The use of a smaller maximum size of RPCC aggregate, together with a lower WCR seems to improve the compressive strength of the concrete. It seems possible to find a modified mixture design using RPCC aggregate that ensures a good quality product.

RPCC material can develop a high friction angle at failure, making this material highly recommended for use in embankments. Moreover, RPCC aggregate can be mixed with a material of lower quality, making its use more economically attractive.

Further studies are needed with larger samples to determine more accurately the relationship between the parameters mentioned above and to implement a similar mixture design method for concrete made with RPCC to that already existent for conventional material.

CHAPTER 1. INTRODUCTION.

The construction of infrastructures related to bridges, highways, water systems, and buildings has been increasing from the beginning of the past century, especially in areas where population density is high. Infrastructures need to be repaired with the pass of the time. In some cases, constructions need to be replaced, because their service life is reached or their original design no longer satisfy the new requirements (population, traffic, or weather). These facts have generated two important issues: first, a growing demand for construction aggregates, and second an increasing production of construction material waste.

In the United States, two billion tons of aggregate are produced per year (1), and more than 2.5 billion tons per year are expected to be consumed in the year 2020 (2). This has raised the concern about the availability of production of the actual natural resource, and the projection of new natural aggregate sources, especially near large population settlements, where the demand for this material is higher. The development of new natural resources involves economic issues, such as transportation costs, as well as environmental concerns, impact in the landscape, and extinction of no renewable resources..

The construction waste only, on the other hand, produced from building demolition is estimated to be 123 million tons per year (2). Historically, the most common method of managing this material has been through disposal in landfills. It is estimated that 50 percent of concrete debris and 20 percent of all asphalt pavements end up in landfills (3). As cost, environmental regulations, and land policies of landfill arise, the concern to seek alternative uses of the waste material also increases.

This situation has led the aggregate industry to begin reclaiming construction waste as an alternative aggregate especially for pavement uses. Additionally, government entities have started promoting this recycling process as an option to natural aggregate, helping extend the life of natural resources, reducing the environmental disturbance around construction site, and reducing the volume of waste to landfill areas.

1. 1. Reclaimed Portland Cement Concrete.

Reclaimed Portland cement concrete (RPCC) consists of high-quality, well-graded aggregates bonded by a hardened cementitiuos paste. This material is manufactured from demolition of Portland cement concrete construction such as roads and runways, and structures such as building and bridges. Portland cement concrete is a widely used construction material. It is defined as a mixture of water, Portland cement and aggregates. The paste (water and cement) represents 25% to 40% of the total volume of the concrete, and it functions as the adhesive and bind the aggregate together to form the concrete. The aggregates consist of natural or manufactured sand, gravel or crushed stone and make up the other 60% to 75% of the total volume of concrete.

In general, when the source of RPCC is from existing concrete curb, sidewalk and driveways sections, RPCC is removed with a backhoe or payloader and is loaded into dump trucks for removal from site. In this case, RPCC may contain 10% to 30% subbase soil material and asphalt pavement.

Aggregate made from RPCC can be used for cement-treated or lean concrete bases, concrete, flowable fill, or asphalt concrete. To be used as an aggregate, RPCC must be free of foreign debris and reinforcing steel. RPCC can also be used as bulk fill material on land or water, as shoreline protection material, as gabion basket fill, or as granular aggregate base for base and trench backfill.

1. 2. Purpose of the Study.

The purpose of this research is to study the behavior of RPCC aggregates when it is included in Portland cement concrete or in embankments. For the first case, slump tests were performed on freshly mixed concrete, and compression tests were performed on hardened concrete. Several batches of concrete were prepared with RPCC and natural aggregate, changing their mixture design parameters, including aggregate sieve distribution (gradation) and water cement ratio. For the second case, shear tests were performed on RPCC aggregate with the objective of obtaining the failure envelope and the friction angle, and evaluating the shear capacity of this material.

This thesis is divided into 5 chapters. Chapter 1, Introduction, contains the general context and the purpose of the study. Chapter 2, Literature Review, is a summary of the relevant concepts related to RPCC material needed in this study. Chapter 3, Materials and Methodology, presents a description of the materials and their preparation for testing, and a summary of the test methods. Chapter 4, Results, contains results of the tests performed on RPCC material, concrete made with RPCC and concrete made with natural aggregates. Chapter 4 also contains the analysis of the results and comments. Chapter 5, Comments and Recommendations, presents the general conclusions of this study, the recommendations about the uses of RPCC aggregates, and suggestion on future research.

CHAPTER 2. LITERATURE REVIEW.

2. 1. Introduction.

The demand of natural aggregate for construction purposes has increased over the years in the United States, as it can be seen in Figure 2.1 (3). This demand depends on two factors: population density and economical development, because higher population ratios and stronger economies imply the improvement of the transportation systems and the production places, including highways, roads, bridges, and buildings.

The substitution of natural aggregate by reclaimed Portland cement concrete (RPCC) could be a convenient solution to satisfy the growing requirement of aggregate. Possible advantages of using RPCC as aggregate include waste reduction, demand of the natural resources decreasing, environmental impact reduction, and energy resources conservation. A study from the U.S. Geological Survey (USGS) (4) established that RPCC is produced from two primary sources: road construction and maintenance debris, and structural construction demolitions. Kelly (2) reported that the substitution of RPCC for construction aggregate mostly takes place in highway construction, where sub-base is its principal destination (68%) and only a minor amount (6%) is used in cement concrete, as it is shown in Figure 2.2

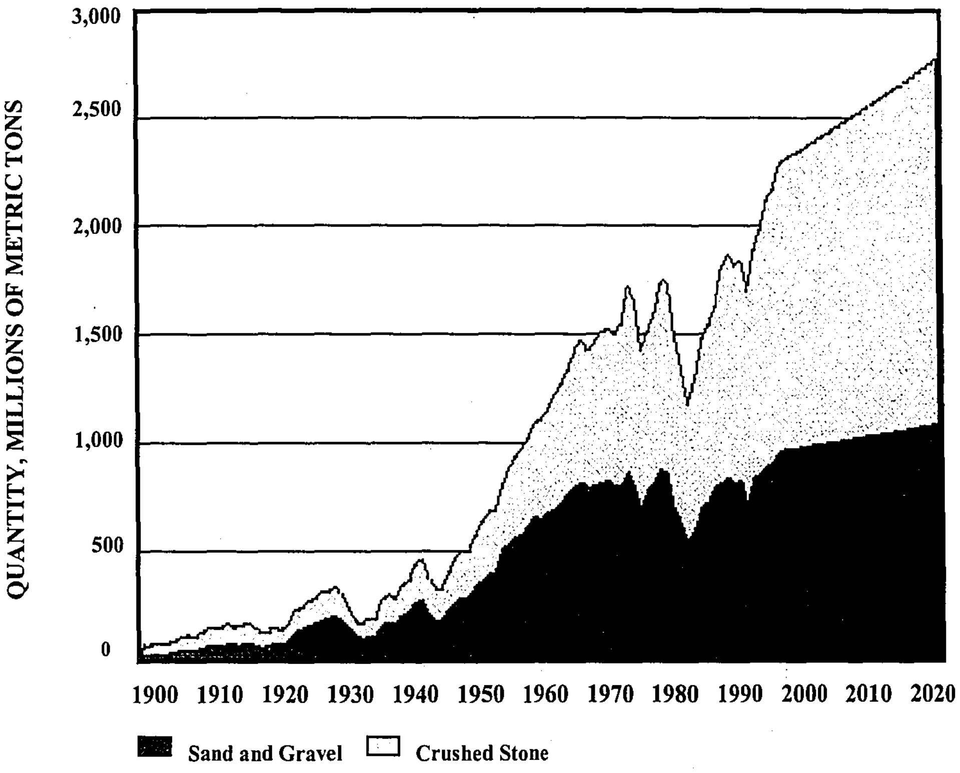

Figure 2.1. Natural Aggregate Consumption in the United States. (Historical and Projected). Tepordei, 1997 (3).

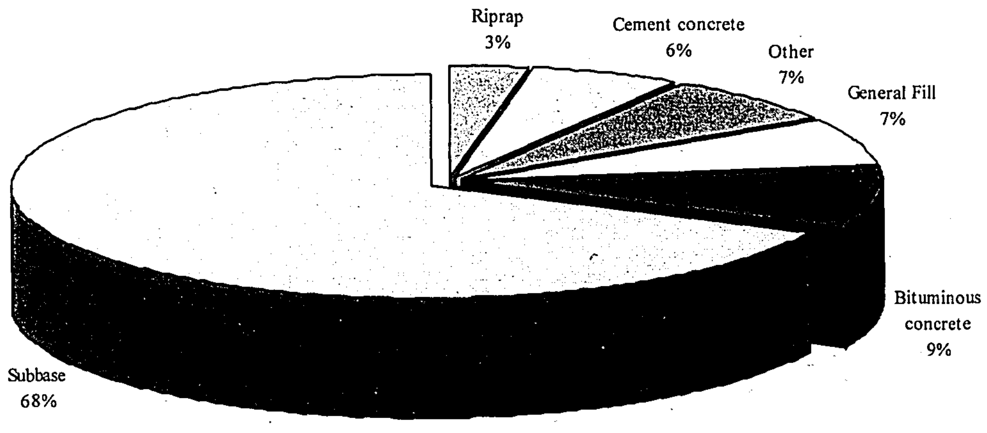

Figure 2.2. End Uses of Reclaimed Cement Concrete. (2).

This author also established that even though the production of reclaimed cement concrete has been increasing, RPCC aggregate represents less than 5% of the total of aggregate required by the construction market as it is indicated in Figure 2.3. This figure compares the conventional and reclaimed cement concrete aggregate supplies for the highway construction market in three categories: road and base, cement concrete, and asphalt concrete.

According to a study made by U.S. Department of Transportation (5), recycling in the European countries occurs when it is economically feasible. It is generally supported by government policies and regulations such as bans on landfilling, lanfill taxes, and natural aggregate taxes. Generally, clear engineering and environmental test method help reduce uncertainty and allow recycled aggregate to compete with natural materials. Where tests and standards are not available, governments usually support recycling by sharing risk. The substitution of natural aggregates by reclaimed cement concrete material involves a series of steps, ranging from the selection of the source of reclaimed concrete and its processing to the quality certification of the final product in which the recycled aggregate is used.

This chapter describes the production of recycled cement concrete, its material properties and the requirements for different uses in highways, including base, subbase, Portland cement concrete pavement and embankment.

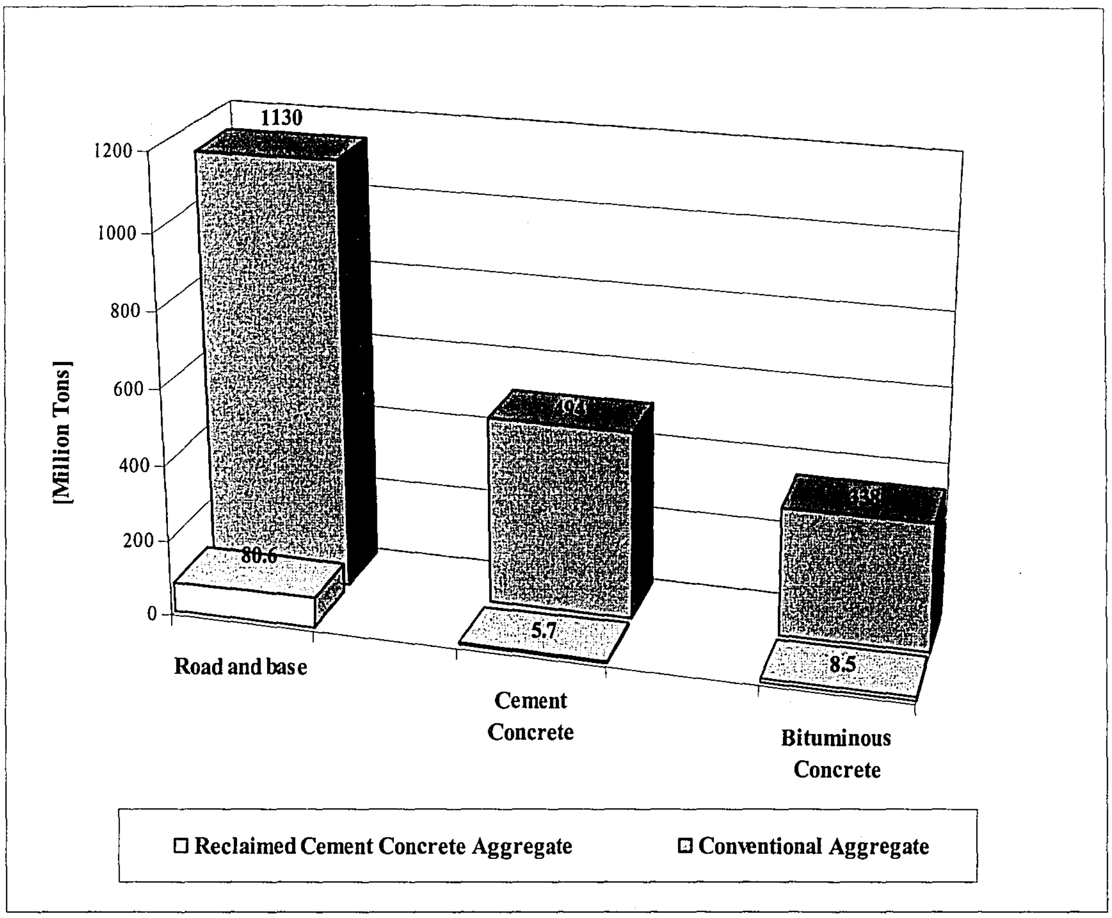

Figure 2.3. End Uses of Aggregates. Conventional Versus Reclaimed Cement Concrete Aggregates, in Million Ton. (2)

2. 2. Production of Reclaimed Cement Concrete.

The raw material used in the production of recycled aggregates comes mainly from demolition of pavements and building. This material is broken into large pieces and transported to the processing plant. Once at the plant and before processing the material, it must be clean, free of contaminants like steel reinforcement bars, wood, and soil. Then, the material goes through three main phases: crushing, sizing, and blending.

2. 2. 1. Processing Plants.

Recycled concrete and asphalt material usually are heterogeneous, having different sizes, shapes, and composition. Therefore, the equipment used to process reclaimed material is required to handle these variations; it must be versatile and able to maintain the production's efficiency for a variety of materials (4). Moreover, the equipment used in recycled aggregate operation may present higher wear levels, and therefore a shorter useful life than a conventional material operation. Jaw/cone combination, horizontal-shaft impactor, and jaw/roll combination are the crushing equipment commonly used in the recycling of RPCC.

Because of the versatility of the equipment in recycled aggregate plants, they can be used to process concrete and asphalt debris as well as natural sand and gravel from natural sources, but conventional aggregate plants usually cannot process efficiently recycled material. Recycling plants can be stationery or mobile. The advantage of mobile plants is that they can be located as close as possible to the source of raw material, decreasing the transportation cost.

2. 2. 2. Plant Operation.

The recycling operation starts when the material comes from demolition projects. If the reclaimed material contains large pieces of concrete, it is necessary to break down these pieces to a maximum size of 16 to 28 inches (40.6 to 71.1 cm.), using hydraulic breakers (6). The material is cleaned from contaminants like steel and wood and used to feed the crushing equipment (primary crushing). After the primary crushing, the material is reduced to 2 to 3 inches (5.1 to 7.6 cm.) and deposited in a belt conveyor. Next, reinforcing steel is removed by a self-cleaning magnet running over the crushed concrete. Then, the reclaimed material is screened in order to separate the usable size portion from the waste portion. The usable portion is sent to a secondary crushing process. This crushing process is necessary to reduce the pieces of reclaimed concrete and produce a finished aggregate of ¾ to 1 ½ inches (1.9 to 3.8 cm.) size. This resultant aggregate has less than 2 percent passing through a No. 200 (75 μm.) sieve. The final product is screened and stockpiled. To avoid segregation of particle size, coarse and fine aggregate are stockpiled, separately. The summary of plant operation is presented in Figure 2.4.

Concrete from Portland cement concrete pavements may be relatively clean after magnetic and hand removing, but this is not the case with all demolished concrete. Other contaminants may be present, including plaster, wood, plastic, asphalt, and other non-metallic materials. Additional cleaning process will be necessary to remove all the potential contaminants, like washing and air shifting.

2. 3. Recycled Aggregate Properties.

It is important to consider that RPCC can be made from a diversity of concrete debris, and it may affect its properties. Therefore, it is strongly recommended to monitor the physical, chemical, and mechanical properties of this material periodically. The U.S. Department of Transportation (7) has made a general description of the physical, chemical, and mechanical properties for RPCC that is summarized below.

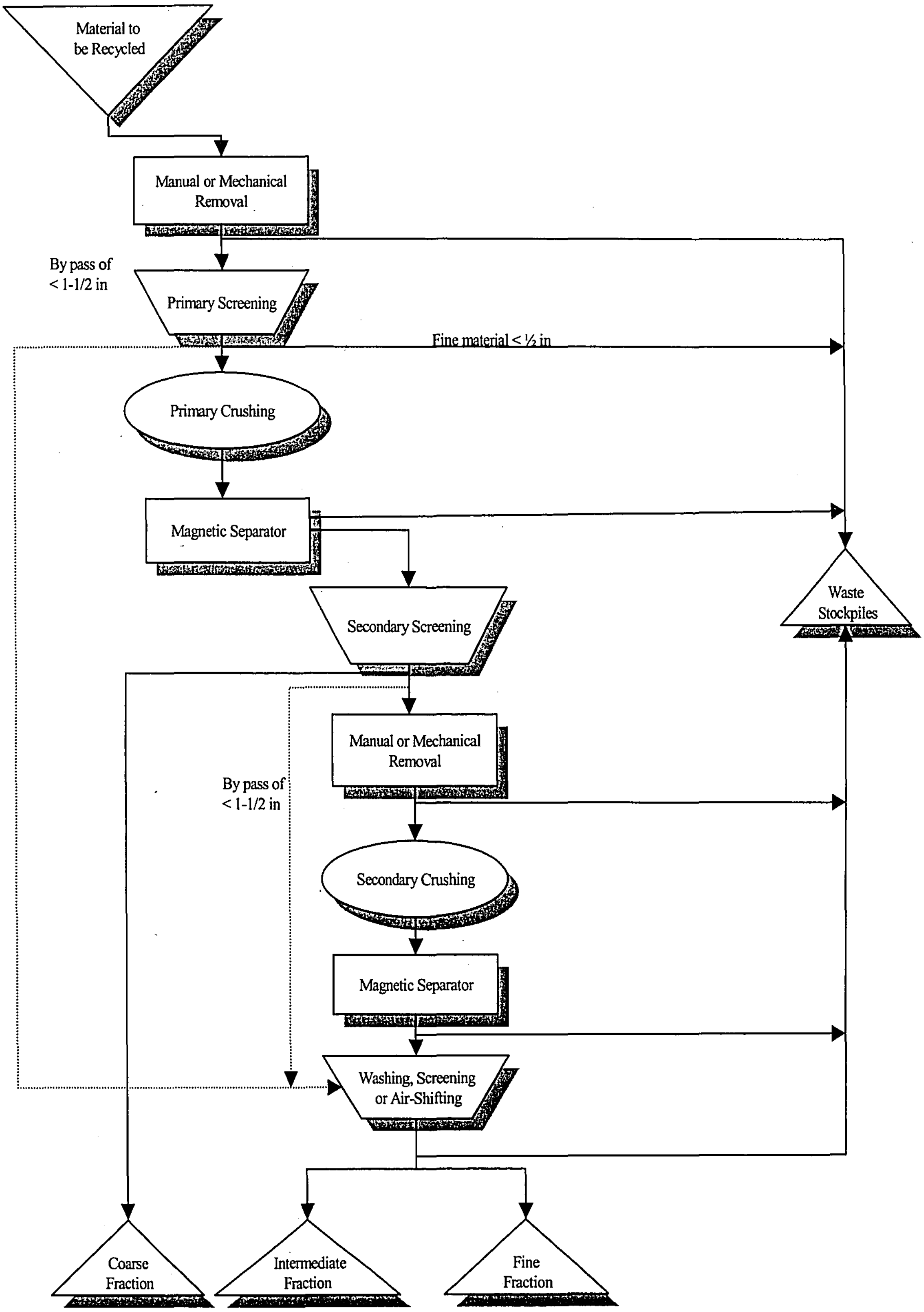

Figure 2.4. Flow Diagram of Reclaimed Cement Concrete Aggregate Production Plant.

2. 3. 1. Physical Properties.

Reclaimed aggregate is usually a combination of natural aggregate and mortar from the recovered concrete. Reclaimed material is obtained after several crushing processes, making the resultant material highly angular in shape. The mortar portion in this aggregate makes its texture rougher, its specific gravity lower, and its water absorption higher than that of natural aggregate with similar size characteristics. Higher absorption values are expected in reclaimed fine aggregate (material passing sieve No. 4 [4.75 mm.]) because the proportion of mortar is bigger than that of the coarse aggregate. Table 2.1 shows a set of typical values for specific gravity and absorption for recycled aggregates as well as natural aggregate listed by the U.S. Department of Transportation (7) and Kosmatka and Panarese (8), respectively.

Table 2.1. Typical Physical Properties of Processed Reclaimed Concrete Aggregate and Natural Aggregate.

Property	Reclaimed Concrete Aggregate (7)	Natural Aggregate (8)
Specific Gravity		
• Coarse Particles	2.2 to 2.5	2.4 to 2.9
• Fine Particles	2.0 to 2.3	
Absorption, %		
• Coarse Particles	2 to 6	0.2 to 4
• Fine Particles	4 to 8	0.2 to 2

2. 3. 2. Chemical Properties.

Chemical properties of RPCC are influenced by cement paste, original aggregate and immersed contaminants of the recovered concrete. The alkalinity in recycled aggregate depends highly on the cement paste. It has a series of calcium-aluminum-silicate compounds, including calcium hydroxide, which is highly alkaline. The pH of RPCC-water mixtures usually exceeds 11. Corrosion can appear in aluminum material and galvanized steel pipes in direct contact with recycled aggregate RPCC and in the presence of moisture as a consequence of the high pH.

Chloride ions may be present in RPCC aggregate; these contaminants come from the applications of deicing salts to roadways surfaces. Chloride ions are associated with corrosion of steel. Sulfates might also be present in RPCC aggregate as a result of the contact with sulfate-rich soils. Sulfate reactions lead to expansive disintegration of cement paste. RPCC may contain aggregate susceptible to alkali-silica reaction (ASR); this reaction may cause expansion and cracking.

2. 3. 3. Mechanical Properties.

Recycled aggregates larger than 4.75 mm (retained by sieve No.4) have favorable mechanical properties for aggregate uses, including good abrasion resistance, good soundness characteristics, and bearing strength. Los Angeles Abrasion Loss values are higher than those of high-quality conventional aggregates. Magnesium sulfate soundness and California Bearing Ratio (CBR) values are comparable to conventional aggregate. Table 2.2 shows a set of typical values for these mechanical properties of reclaimed concrete as well as natural aggregate (6, 7).

2. 4. Use of RPCC Material in Highways.

The use of RPCC in highway construction has economic advantages. Recycled aggregate has usually a lower specific gravity than natural aggregate. As a consequence, for a given specified coarse aggregate content greater volumes of RPCC material can be obtained compared to conventional aggregate. In addition, mobile processing plants of recycling aggregate can be installed as near construction sites, decreasing considerably the transportation costs for large projects.

Table 2.2. Typical Mechanical Properties of Processed Reclaimed Concrete Material and Natural Aggregate.

Property	**Reclaimed Concrete Aggregate. [%](7)**	**Natural Aggregate. [%](6)**
Los Angeles Abrasion Loss (ASTM C131) • Coarse particles	20-45	20 to 25
Magnesium Sulfate Soundness Loss (ASTM C88) • Coarse particles • Fine particles	4 or less Less than 9	3 or less 6 to 8
California Bearing Ratio (CBR)	94 to 148	130 to 180

It can be seen from Figure 2.2 that the principal destination of reclaimed cement concrete in pavement construction are: subbase, including granular and stabilized base, bituminous concrete, Portland cement concrete and general fill. RPCC aggregates may potentially be used in flowable fill and surface treatment. Recommendations and considerations about the use of reclaimed concrete in granular base, Portland cement concrete, and embankment are presented below.

2. 4. 1. Granular Base.

A granular base consists of a prepared and compact material, which is placed in layers below Portland cement or asphalt concrete pavements. The largest proportion of recycled aggregate is used in base and subbase applications (see Figure 2.2). According to U.S department of Transportation (9), twenty states of U.S. have accepted the use of RPCC aggregates in base and subbase, including Arizona, California, Colorado, Florida, Indiana, Iowa, Louisiana, Maryland, Massachusetts, Minnesota, Missouri, Nebraska, New Jersey, New York, North Dakota, Ohio, Pennsylvania, Rhode Island, South Carolina, and Texas. Illinois and Pennsylvania have specifications for RPCC aggregate uses in granular base, meanwhile other states are conducting or have proposed research that involves the use of reclaimed concrete material in granular base, like Arizona, Iowa, Louisiana, Michigan, Missouri, and Nebraska. A summary of the considerations and recommendations provided by the U.S Department of Transportation (9) are presented below.

2. 4. 1. 1. Considerations for Using RPCC in Granular Base.

RPCC properties generally exceed the minimum requirements for conventional granular aggregate. Because RPCC aggregate is crushed material, this aggregate "lock up" well in granular base application, providing good load transfer when placed on weaker sub grade. Some other favorable features of RPCC material in granular base applications are: the ability of stabilized wet, soft, underlying soils at early construction age, good durability, good bearing strength, good drainage characteristics, good stability and little postcompaction settlement.

Special considerations are made when RPCC aggregate is used in granular base course applications in conjunction with subdrains, with the intent of preventing the leachate precipitation. The recommended procedures are: to wash the RPCC aggregate, and to ensure that any geotextile fabric surrounding the subdrains does not intersect the drainage path from the base course (to avoid potential plugging with fines). There have been reports of tufa-like precipitates (white, powdery precipitate) from unsuitable or improperly processed recycled concrete aggregate that have clogged subdrains and blinded geotextile filters.

2. 4. 1. 2. Requirements for Using RPCC in Granular Base.

RPCC material must be crushed and screened to satisfy AASTHO M147 (10) and ASTM D2940 (11). It is recommended the use of the standard AASHTO pavement structural design procedure for granular base when RPCC aggregates are incorporated. It is suggested that, for construction purposes, placing, compacting, and quality control procedures of reclaimed concrete material follow the same method and equipment as those of conventional aggregates. The material handling and storage, though, needs additional care to avoid segregation of coarse and fine aggregate. Some jurisdictions require that stockpiles be separated from water courses to avoid contamination from lecheate that is highly alkaline. Regulations for some states like Ohio require that RPCC aggregate be washed in order to reduce potential tufa formation.

2. 4. 2. Portland Cement Concrete.

U.S Department of Transportation (12) established that reclaimed concrete material can be used as coarse aggregate and/or fine aggregate in Portland cement concrete pavements. High quantities of fine RPCC aggregate (more than 10 to 20%) can produce a reduction in the concrete quality due to the elevated level of absorption of this material, needing more water in order to maintain an adequate workability of the concrete mix.

Several states have special specifications covering the RPCC aggregate uses, including Colorado, Connecticut, Illinois, Indiana, Iowa, Louisiana, Michigan, Montana, North Dakota, Oklahoma, and Wyoming. General considerations and requirements given by the U.S.D.O.T (12) are presented below.

2. 4. 2. 1. Considerations for Using RPCC in PCC.

The shape of recycled aggregate (highly angular) increases the strength of the mix and at the same time it can reduce its workability. The use of fine RPCC aggregate also reduces the concrete mixture workability because of the high absorption and high angularity of this kind of aggregate.

It is expected that Portland cement concrete made with recycled aggregate develops lower strength than the concrete made with conventional aggregate. Compressive strength could be reduced up to 25%, flexure strength up to 10%, and the static and dynamic modulus of elasticity up to 40 % for mixture with the same characteristic (water cement ratio and slump). On the other hand, the incorporation of RPCC aggregate improves the damping capacity up to 30%. The reduction in strength associated to the incorporation of reclaimed concrete aggregate depends on the origin of the concrete. Table 2.3 shows the compressive strength of concrete made from natural and recycled aggregates. In general, there is a reduction in strength as a concrete is produced from reclaimed aggregate.

The mortar in the reclaimed concrete aggregate provides a proper air void system to the concrete resulting in a good resistance to freeze-thaw cycles. Recycled material that comes from pavement can contain deleterious substances like chlorides as a result of the deicing salt application on old roads. The high content of chloride in this aggregate can induce corrosion of reinforcing steel embedded in new concrete. Usually, the content of chloride in recycled aggregate is below the threshold value (2.4 kg/m^3 recommended by the American Concrete Pavement Association)

2. 4. 2. 2. Requirements for Using RPCC in PCC.

It is established that RPCC aggregate can be considered as conventional aggregate for Portland cement concrete mixtures, therefore RPCC aggregate needs to satisfy the following standard requirements:

- AASTHO M6, " Fine Aggregate for Portland Cement Concrete"
- AASTHO M43, " Size of Aggregate for Road and Bridge Construction"
- AASHTO M80, " Coarse Aggregate for Portland Cement Concrete".

Table 2.3. Compressive Strength in Psi (MPa) of Concrete Made from Natural and Recycled Aggregate Concrete. (6).

H	H/H	H/M	H/L	M	M/H	M/M	M/L	L	L/H	L/M	L/L
8,870 (61.16)	8,178 (56.39)	7,150 (49.30)	5,020 (36.61)	5,090 (35.09)	4,990 (34.40)	4,748 (32.74)	3,900 (26.89)	2,150 (14.82)	2,000 (13.79)	2,100 (14.48)	1,940 (13.38)
8,870 (61.16)	8,800 (60.68)	-	-	5,250 (36.20)	-	5,220 (35.99)	-	2,100 (14.48)	-	-	1,970 (13.58)
8,790 (60,60)	8,480 (58.47)	-	-	5,220 (35.99)	-	4,810 (33.16)	-	2,180 (15.03)	-	-	1,860 (12.82)

Note:

1. H= High strength concrete; M= Medium strength concrete; L= low strength concrete.
2. H/H= High strength concrete made with recycled aggregate from high strength concrete.
   H/M= High strength concrete made with recycled aggregate from medium strength concrete.
   H/L= High strength concrete made with recycled aggregate from low strength concrete.

It is highly probable that RPCC material comes from different sources, in such case recycled aggregate should either be blended with other aggregate or separately processed and placed in separate stockpiles to ensure uniformity of RPCC aggregate properties.

It is recommended that the level of contamination and potential reactivity of RPCC be controlled, and it is required to satisfy the same limits as those of natural aggregates. The level of impurities, such as sulfate and chloride ions, alkali-reactive aggregate and freeze-thaw expansion of large aggregate also needs to be controlled in order to ensure strength and durability requirements of the concrete.

Trial batches of concrete mixture and the necessary adjustment should be done in order to ensure the achievement of concrete mixture requirements. It is strongly recommend maintaining the recycled aggregate wet, otherwise it will absorb water from the concrete mix because of its high absorption rate. The higher absorption rate in fine aggregate can affect workability, strength, and finishability in Portland cement concrete mixtures. The U.S. Department of Transportation (8) established that RPCC fines blended with natural sand at substitution rates of 10 to 20 percent has resulted in satisfactory performance and preparation of trial mixes are often required to find the optimum substitution rate.

This entity also recommends AASHTO rigid pavement thickness design procedures for the structural design of pavement incorporating recycled aggregate. For construction purposes, the same equipments and procedures may be used to batch, mix, transport, place, and finish the concrete as well as material handling and storage, and compacting, for mixture made with natural as recycled aggregate.

Quality control processes for Portland cement concrete with natural aggregate can be used for concrete with recycled aggregate. Fresh concrete mixes need to be tested at the time of placement using standard methods, including slump (ASTM C143), air content (ASTM C138, C173, C 231), and temperature (ASTM C 1064). It is important to monitor the hardened concrete strength properties by casting cylinders and testing them using standard method, including compressive strength (ASTM C39) and splitting tensile tests (ASTM C78). Prisms can be used to test flexural strength following ASTM C 496 standard method.

2. 4. 3. Embankment or Fill.

An embankment is a structure of soil, soil aggregate, or rock, with the purpose of raising the grade of the roadway or railway above the level of the existing surrounding ground surface. U.S Department of Transportation (13) establishes that reclaimed material requires a minimal processing to satisfy the conventional soil and aggregate physical requirements for embankment or fill material. Usually, the properties of recycled material are overqualified for filling purposes. RPCC aggregate has attributes that make it attractive to use: it has high friction angle, good bearing strength, negligible plasticity, drainage characteristics, and it is not susceptible to frost (13).

2. 4. 3. 1. Considerations for Using RPCC in Embankment.

In general, RPCC aggregate has good durability and resistance to weathering and erosion, good stability and little postcompaction settlement. RPCC aggregate can induce corrosion in aluminum or galvanized steel pipes in presence of moisture due to its high alkalinity. Recycled concrete material that comes from composite pavements may contain some reclaimed asphalt pavement. It is recommended that the content of this material be limited to a rate of 20% in order to prevent a reduction in bearing strength.

2. 4. 3. 2. Requirements for Using RPCC in Embankment.

The U.S. Department of transportation (9) established that RPCC material must satisfy the gradation requirement on the following standard specifications:

- AASTHO M145 (10), "The classification of soils and soil-aggregate mixture for highway construction purpose".
- ASTM D2940 (11), "Standard specification for graded aggregate material for bases or subbases for highways or airports".

The same potential for tufa-like precipitates to leach from recycled aggregate in granular base application should be considered in embankment and fills. To prevent this tufa formation, some jurisdictions require washing the aggregate to remove the dust and use only RPCC aggregate not containing significant quantities of unhydrated cement or lime (13).

For structural design purposes, the standard specifications and methods for embankment and fill using natural aggregate can be used when recycled aggregate is incorporated. It is suggested that for construction purposes, the material handling and storage, needs additional care to avoid segregation of coarse and fine aggregate. Some jurisdictions require that stockpiles be separated from water courses to avoid contamination from lecheate that is highly alkaline. Special care is required to compact RPCC aggregate in order to achieve its maximum density value because of its high angularity. For quality control purposes, the same standard test used with conventional aggregate can be applied to embankment and fill made with recycled concrete material.

CHAPTER 3. MATERIALS AND METHODOLOGY.

3. 1. Introduction.

The research was addressed to the study of the incorporation of Reclaimed Portland cement concrete (RPCC) in Portland cement concrete pavement and embankments. For Portland cement concrete, slump and compression tests were performed with the purpose of studying and comparing the properties of freshly mixed and hardened Portland cement concrete made with RPCC as well as natural aggregate, using the same mixture design and specifications. For the second case, the use of recycled concrete in embankment, shear tests were performed with the objective of determining the shear capacity of this material, i.e. calculating its failure envelope and its angle of friction at failure. The present chapter presents a description of the work made for this research, including material description, aggregate properties, material preparation, and testing procedures.

3. 2. Material Description.

3. 2. 1. Reclaimed Portland Cement Concrete Coarse Aggregate.

An aggregate producer in Maryland donated the RPCC aggregate used in this research. The recycled aggregate was identified as RC-57 (Reclaimed concrete #57) and it met the requirements for size #57 specified in ASTM C33 (14). Table 3.1 contains the material properties of RPCC. Specific gravity and absorption were determined in laboratory and they were included in Chapter 4, Section 4.2.1. Table 3.2 presents the sieve analysis of the aggregate. From visual observation as shown in Figure 3.1, the material was highly angular in shape.

The recycled aggregate was sieved, separated, and stored by individual sizes. All the contaminated particles were removed through sieving and washing processes. RPCC aggregate was recombined later according to the necessities of the mixture design and following the grading proportion specified in Table 3.3.

Table 3.1. Crushed Concrete Recycled Aggregate Physical and Mechanical Properties.

Property	Value
Plastic index	Non-Plastic
Loss Angeles Abrasion Loss	35.9%
Soundness. (By use of sodium sulfate. ASTM C88)	6.6%

Table 3.2. Sieve Analysis of the Crushed Concrete Recycled Aggregate.

Sieve Size		Crushed Concrete recycled Material	ASTM C33 Requirements (14)
in	mm	% passing by weight	% passing by weight
1 ½"	37.5	100	100
1"	25.0	96	95-100
½"	12.5	27	25-60
#4	4.75	5	0-10
#8	2.36	2	0-5

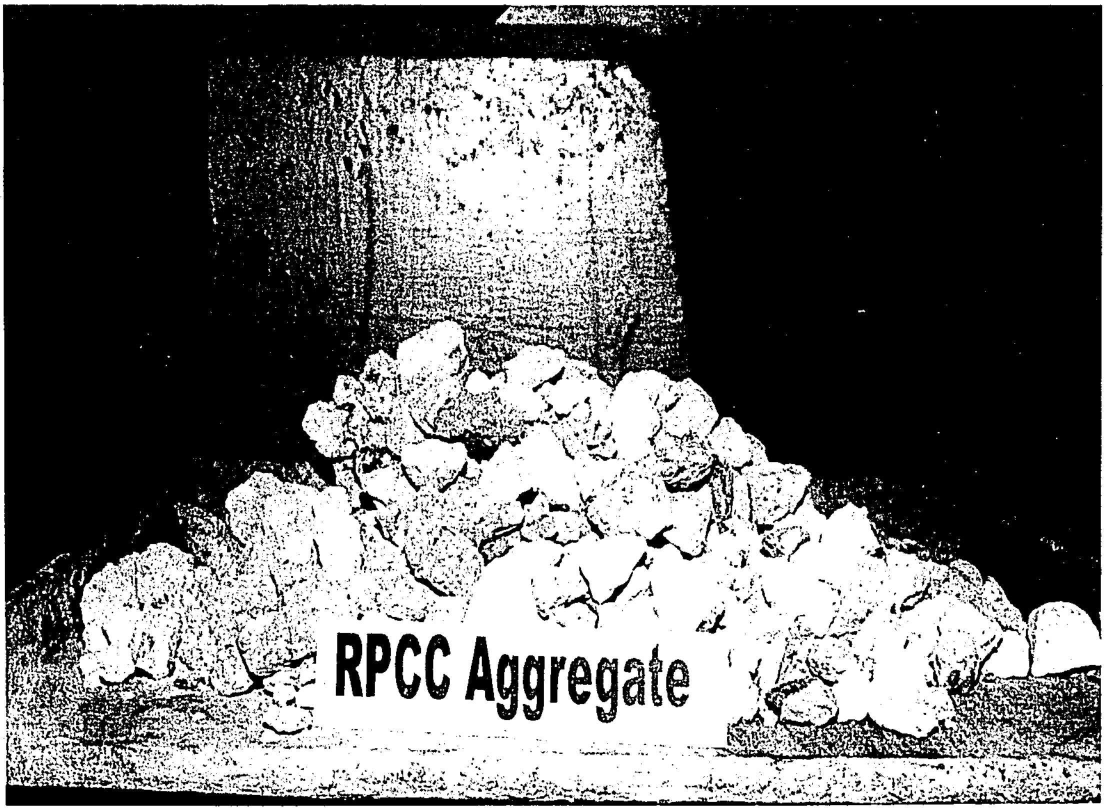

Figure 3.1. RPCC Aggregate.

3. 2. 2. Natural Coarse Aggregate.

The natural aggregate used in concrete mixture was the material available in the laboratory. It corresponded to coarse aggregate type 2 B according to Pennsylvania Department of Transportation (15). This material was sieved, separated, and stored by individual sizes. Natural aggregate was recombined later according to the necessities of the mixture design and following the grading proportion specified in Table 3.3.

Specific gravity and absorption were determined in laboratory and they were included in Chapter 4, Section 4.2.1. The physical appearance of this material can be seen in Figure 3.2.

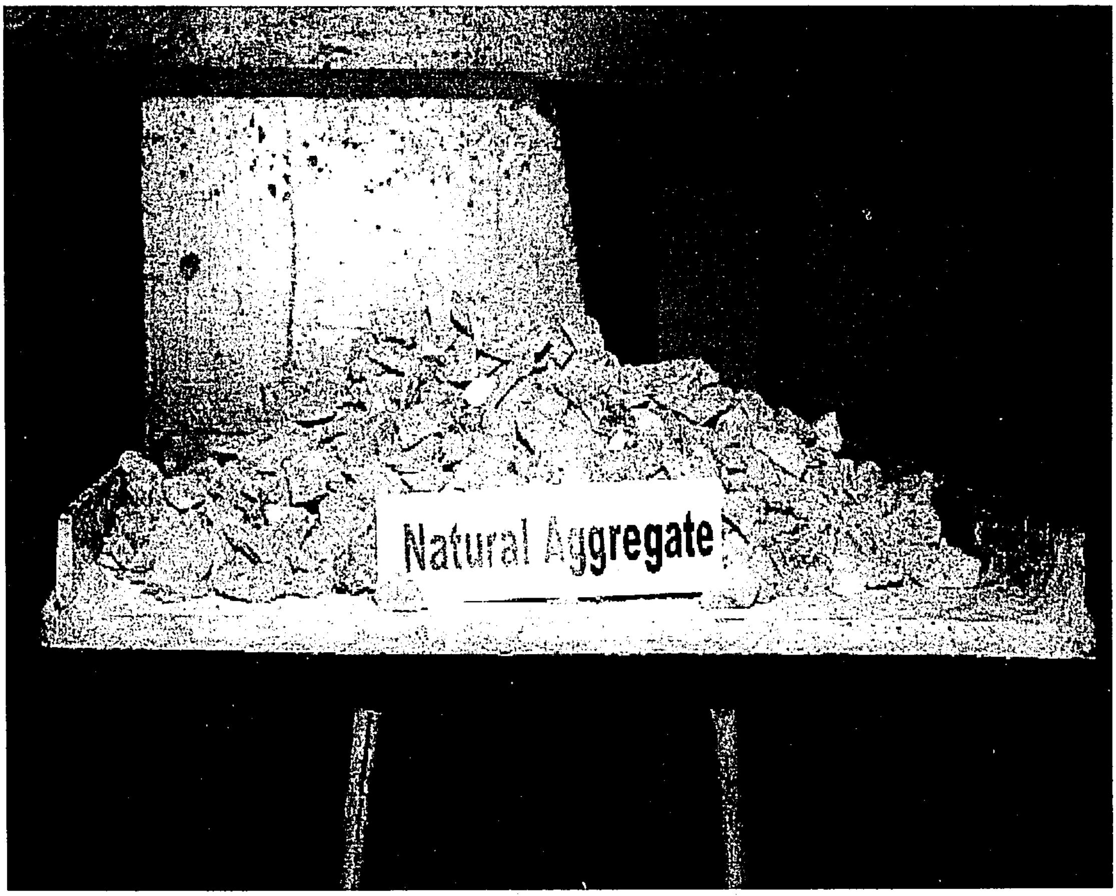

Figure 3.2. Natural Aggregate.

3. 2. 3. Natural Fine Aggregate.

The natural fine aggregate used was that available in the laboratory. It corresponded to Cement Concrete Sand (type A) according to Pennsylvania Department of Transportation (15). A sieve analysis was made to fine aggregate following ASTM C136 (16). Four samples were taken using the technique named Quartering which is explained in ASTM C702 method B (17). The minimum size requirement of the sample was 300 gr or 0.661 lb. The sieves used for the grading analysis corresponded to: 3/8”(9.38 mm), No. 4 (4.75 mm), No.8 (2.36 mm), No. 16 (1.18 mm), No. 30 (600 µm), No.50 (300 µm), and No. 100(150 µm).

Specific gravity and absorption were assumed as 2.64 and 0.7 % respectively. These values represent average magnitudes for specific gravity and absorption (8).

3. 2. 4. Gradation of Coarse Aggregates.

Three gradations were specified in this section. They are presented in Table 3.3 and shown in Figures 3.3, 3.4, and 3.5. They corresponded to No.57, No. 67, and No. 7 under the ASTM C33 (14) designation. The grading proportions were estimated based on the maximum size of the aggregate needed for the concrete batches, the material availability, and the requirements established by ASTM C33 specification.

Table 3.3. Gradation of Coarse Aggregate for Different Maximum Sizes of the Aggregate.

Size Number		**No. 57**	**No. 67**	**No. 7**
Maximum Size, in (mm).		1 (25.0)	3/4 (19.0)	1/2 (12.5)
Sieve Size				
in	mm	% passing by weight	% passing by weight	% passing by weight
1 1/2"	37.5	100	100	100
1"	25.0	96	100	100
3/4"	19.0	62	95	100
½"	12.5	27	55	90
3/8"	9.50	13	20	50
No.4	4.75	0	0	0
No.8	2.36	0	0	0

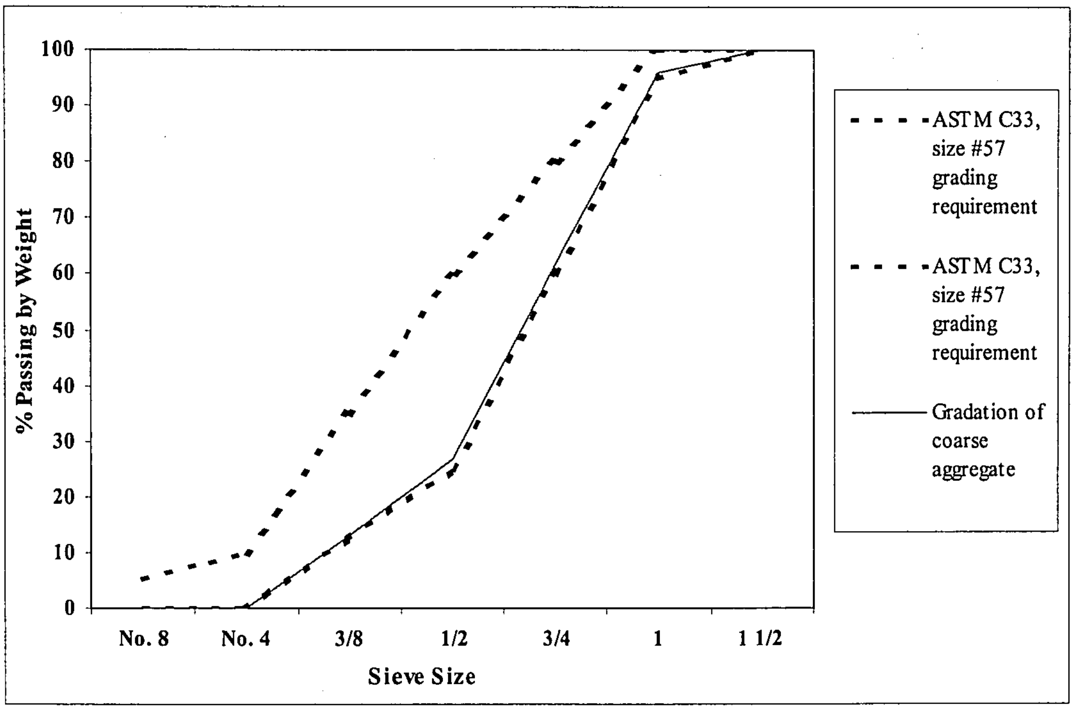

Figure 3.3. Gradation of Coarse Aggregate Size #57. According to ASTM C33 (14).

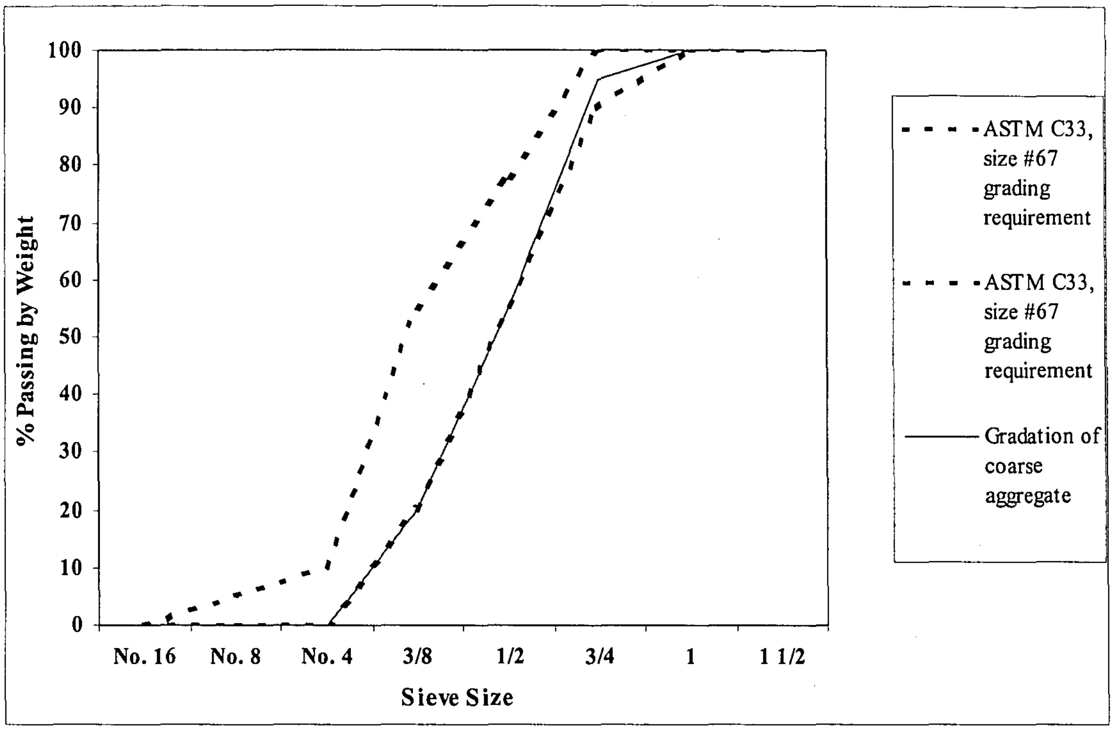

Figure 3.4. Gradation of Coarse Aggregate Size #67. According to ASTM C33 (14).

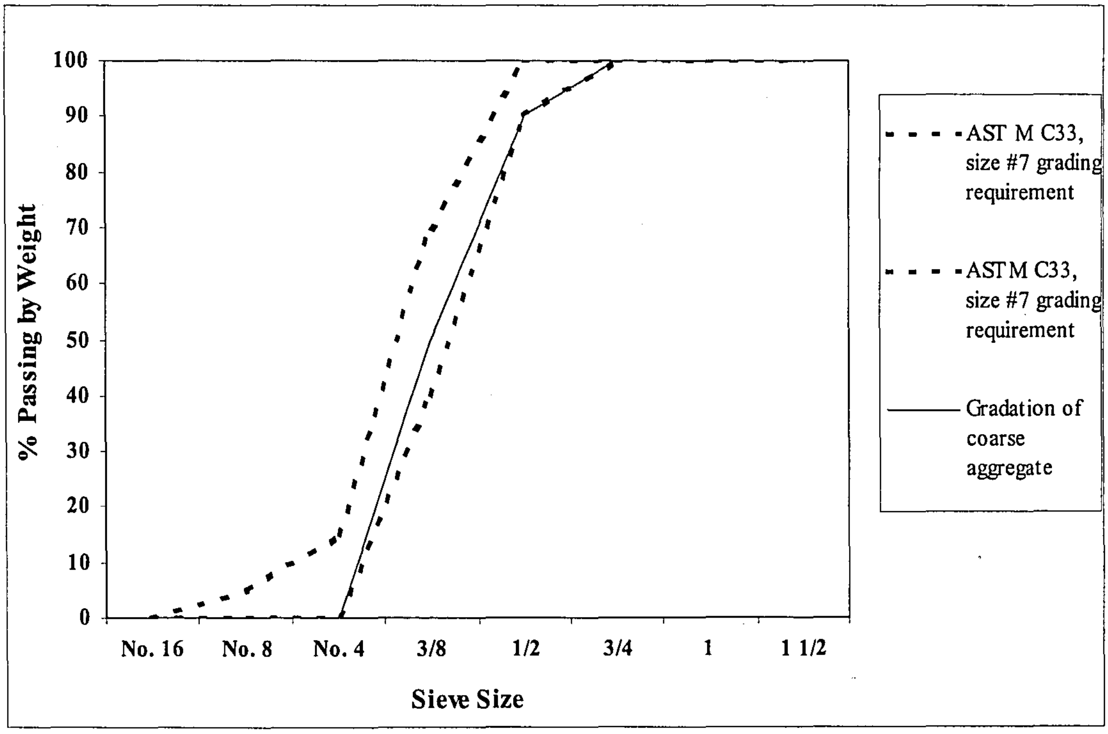

Figure 3.5. Gradation of Coarse Aggregate Size # 7. According to ASTM C33 (14).

3. 2. 5. Specific Gravity and Absorption.

ASTM C 127 (18) standard test method was used to determine Specific Gravity and Absorption of RPCC and Natural coarse aggregates. These two values were used afterward in the mixture design method. Two samples were tested, a RPCC and a natural aggregate sample of 9.20 lb (41.7 kg) saturated-surface-dry weight. The samples corresponded to a material No.57, with maximum size of the coarse aggregate of 1 in (2.5 cm) and their grading description is shown in Table 3.3 and Figure 3.3.

The test method consisted in immersing the samples in water for approximately 24 hours. Then, the samples were removed from the water and dried until the water from the surface of the particles disappeared. After this, the samples were weighed, corresponding to saturated surface dry weight (B). Next, the samples were weighed while they were submerged in water, obtaining the saturated weight in water(C). Finally, the samples were oven dried and weighted (oven dry weight in air, A).

Specific gravity and absorption values were calculated as follows:

- Bulk Specific Gravity, SG.

$$SG = \frac{A}{(B-C)} \tag{3.1}$$

- Bulk Specific Gravity (saturated-surface-dry), $SG_{ssd.}$

$$SG_{ssd} = \frac{B}{(B-C)} \tag{3.2}$$

- Apparent Specific Gravity, ASG.

$$ASG = \frac{A}{(A-C)} \tag{3.3}$$

- Absorption, Abs [%].

$$Abs = \left(\frac{(B-A)}{A}\right) * 100 \tag{3.4}$$

3. 4. Portland Cement Concrete (PCC).

Portland cement concrete is made from three principal components: Aggregate, cement, and water. In this study, batches of PCC were made with recycled as well as natural coarse aggregate in order to study changes in properties of freshly mixed and hardened PCC. The properties to study were slump, for freshly mixed concrete, and compressive strength (f'c) for hardened concrete. The mixture design of each batch was based on the absolute volume method (8).

Once the batches were made, a slump test was performed on freshly mixed concrete following the standard method given by ASTM C143 (19), (see section 3.4.3). Next, cylindrical concrete specimens were cast and cured following the standard method given by ASTM C192 (20) (see section 3.4.4). The cylinders were tested in compression to obtain the f'c (compressive strength) at certain ages of the concrete. Compression tests were made according to the standard method specified in ASTM C39 (21).

3. 4. 1. Batches.

Three classes of batches were prepared for both, natural and RPCC coarse aggregates. These are described as follows:

1. **Batches 1.** These batches were specified with a water cement ratio equal to 0.48 and coarse aggregate No.57 (maximum size of the aggregate = 1 in.). A slump test was applied to batches made from natural coarse aggregate (Batches 1N) and RPCC coarse aggregate (Batches 1RPCC). A total of 24 cylindrical concrete specimens were cast, 12 from Batches 1N and 12 from Batches 1RPCC. The cylinders were subjected to compression test at 3, 7, 14, and 28 days. The objective of the compressions tests was to study the relationship between compressive strength versus age of concrete made with recycled and made with natural aggregates, and then compare the results.

2. **Batches 2.** These batches were specified with coarse aggregate No.57 (maximum size of the aggregate = 1 in.). Five water cement ratios were also specified, WCR =0.42, 0.44, 0.45, 0.46, and 0.48. A slump test was applied to batches made from natural coarse aggregate (Batches 2N) and RPCC coarse aggregate (Batches 2RPCC). A total of 54 specimens were cast, 27 from Batches 2N and 27 from Batches 2RPCC. The cylinders were subjected to compression test at 28 days. The objective of the tests was to study the relations between slump and WCR, compressive strength versus slump, and

compressive strength versus WCR made with recycled and made with natural aggregates, and then compare the results.

3. **Batches 3.** Three coarse aggregate were specified for these batches: No.57, No.67, and No.7 (maximum size of the aggregate 1, ¾, and ½ inch respectively). For each specified coarse aggregate, three Water Cement Ratio were established, WCR =0.44, 0.47, and 0.50. A slump test was applied to batches made from natural coarse aggregate (Batch 3N) and RPCC coarse aggregate (Batch 3RPCC). A total of 54 specimens were cast, 27 from Batches 3N and 27 from Batches 3RPCC. The cylinders were subjected to compression test at 28 days. The objective of the tests was to study the relation between compressive strength versus maximum size of the aggregate of concrete made with recycled and made with natural aggregates, and then compare the results.

Table 3.4 summarizes the batches identification number and their design parameters.

Table 3.4. Batch Identification Numbers and their Design Parameters.

No	Batch Identification Number	Batch	Maximum Size		Water Cement Ratio
			[in]	[mm]	
1	**B1R-1-0.48**	1RPCC	1	25.0	0.48
2	**B1N-1-0.48**	1N	1	25.0	0.48
3	**B2R-1-0.42**	2RPCC	1	25.0	0.42
4	**B2R-1-0.44**	2RPCC	1	25.0	0.44
5	**B2R-1-0.45**	2RPCC	1	25.0	0.45
6	**B2R-1-0.46**	2RPCC	1	25.0	0.46
7	**B2R-1-0.48**	2RPCC	1	25.0	0.48
8	**B2N-1-0.42**	2N	1	25.0	0.42
9	**B2N-1-0.44**	2N	1	25.0	0.44
10	**B2N-1-0.45**	2N	1	25.0	0.45
11	**B2N-1-0.46**	2N	1	25.0	0.46
12	**B2N-1-0.48**	2N	1	25.0	0.48
13	**B3R-1-0.44**	3RPCC	1	25.0	0.44
14	**B3R-1-0.47**	3RPCC	1	25.0	0.47
15	**B3R-1-0.50**	3RPCC	1	25.0	0.50
16	**B3R-3/4-0.44**	3RPCC	¾	19.0	0.44
17	**B3R-3/4-0.47**	3RPCC	¾	19.0	0.47
18	**B3R-3/4-0.50**	3RPCC	¾	19.0	0.50
19	**B3R-1/2-0.44**	3RPCC	½	12.5	0.44
20	**B3R-1/2-0.47**	3RPCC	½	12.5	0.47
21	**B3R-1/2-0.50**	3RPCC	½	12.5	0.50
22	**B3N-1-0.44**	3N	1	25.0	0.44
23	**B3N-1-0.47**	3N	1	25.0	0.47
24	**B3N-1-0.50**	3N	1	25.0	0.50
25	**B3N-3/4-0.44**	3N	¾	19.0	0.44
26	**B3N-3/4-0.47**	3N	¾	19.0	0.47
27	**B3N-3/4-0.50**	3N	¾	19.0	0.50
28	**B3N-1/2-0.44**	3N	½	12.5	0.44
29	**B3N-1/2-0.47**	3N	½	12.5	0.47
30	**B3N-1/2-0.50**	3N	½	12.5	0.50

3. 4. 2. Mixture Design.

Several batches were prepared according to the absolute volume method (8). The first step was to define the average design compressive strength of design (f'c) and the required average compressive strength of concrete (f'cr). All batches had a specified f'cr equals to 5000 psi (34.5 MPa). The next step was to select the water cement ratio from Table 3.4 and the expected slump. From these values the content of water, cement, and coarse aggregate could be determined using data given by the method (8). These quantities were expressed in pounds needed to make a cubic yard of concrete. Fine aggregate content was calculated from equation 3.5 and 3.6.

$$FC_{volume} = \left(1 - \left(\frac{WC_{weight}}{SG_{water} * \gamma_{water}} + \frac{CC_{weight}}{SG_{cement} * \gamma_{water}} + \frac{CAC_{weight}}{SG_{coarse} * \gamma_{water}}\right)\right) \quad (3.5)$$

$$FC_{weight} = FC_{volume} * SG_{fine} * \gamma_{water} \quad (3.6)$$

FC_{volume}: Volume of fine aggregate to complete a cubic yard of concrete.

WC_{weight}: Quantity of water in a cubic yard of concrete, [lb].

CC_{weight}: Cement content in a cubic yard of concrete, [lb].

CAC_{weight}: Coarse aggregate content in a cubic yard of concrete, [lb].

FC_{weight}: Fine content in a cubic yard of concrete, [lb].

SG_{water} : Specific gravity of water.

SG_{cement}: Specific gravity of cement.

SG_{coarse}: Specific gravity of coarse aggregate.

SG_{fine}: Specific gravity of fine aggregate.

γ_{water}: Unit weight of water, [lb. per cu yard].

3. 4. 3. Cylindrical Concrete Specimens.

Cylindrical concrete specimens were made according to ASTM C192 (20) specifications. The cylinders were tested to maximum compressive strength. Molds for the specimens were 4 in (10.2 cm) of diameter by 8 in (20.4 cm) height. Figure 3.6 and Figure 3.7 show typical cylindrical specimens made with natural and recycled aggregates, respectively. Three specimens were made from each batch specified in Table 3.4 with a total of 132 cylinders.

The casting process consisted in placing a layer of concrete in a mold corresponding to approximately 1/3 of its volume. Next, concrete was rodded by 25 uniformly distributed strokes using a rod of 3/8 inch (0.95 cm) of diameter. Filling and consolidation procedures were repeated two more times. Finally, the cylinder was finished at the top to produce an even surface. The curing process was made following the instructions given in ASTM C192 (20). Once the specimens were finished, they were covered with a plastic sheet to prevent evaporation for 24 hours. After this time, the cylinders were put in a water storage tank until they turned the specified age for the compression test. Figure 3.8 shows the water storage tank with the specimen inside. All specimens were stored together. The date and an identification number were provided to each cylinder in order to distinguish the individual batches concrete characteristics where they were made.

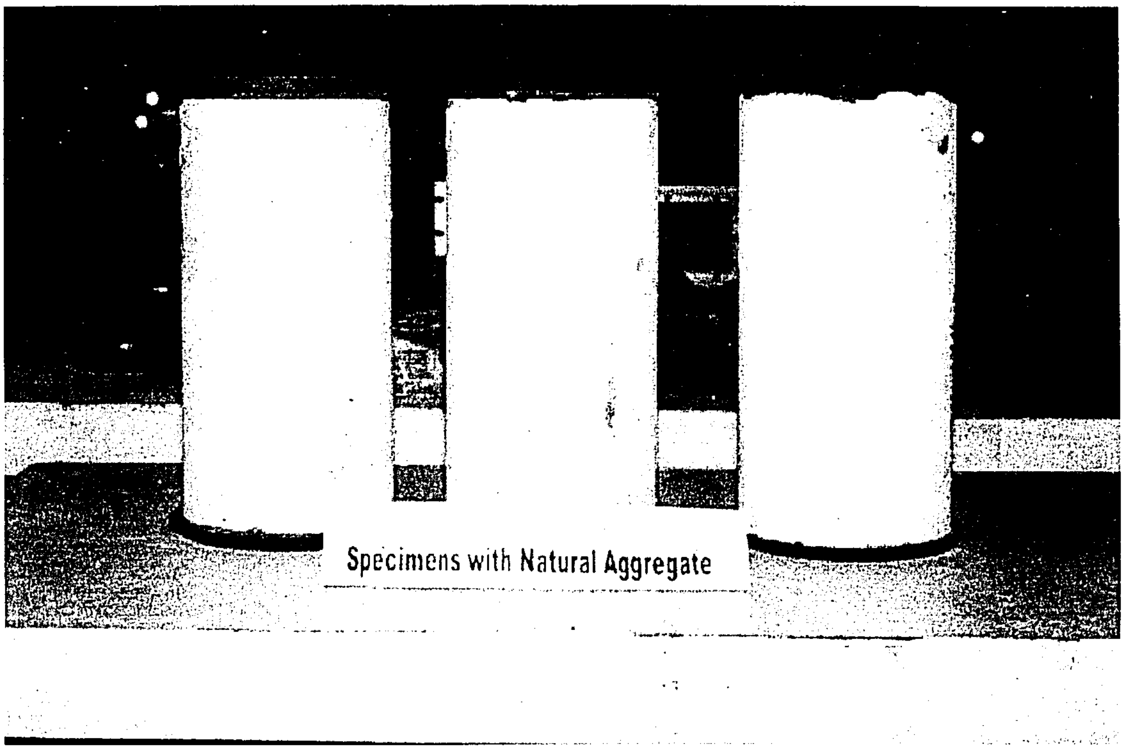

Figure 3.6. Cylindrical Concrete Specimens Made with Natural Aggregate.

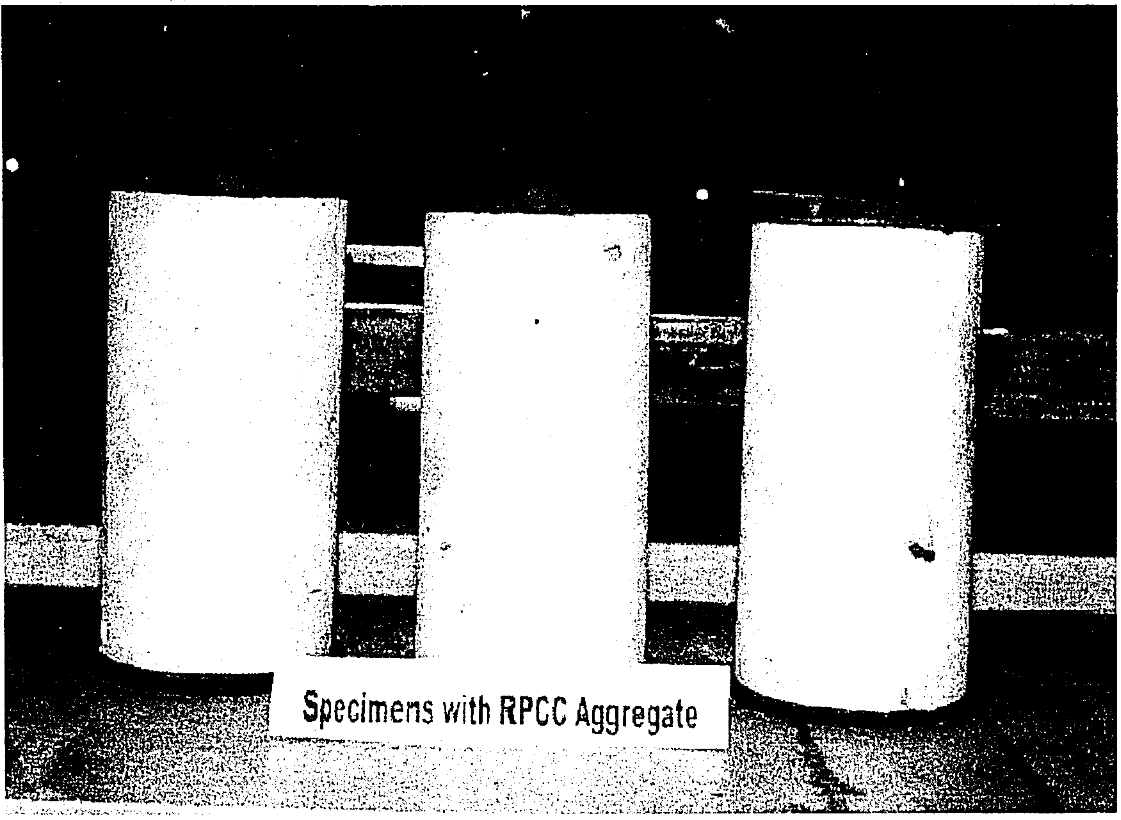

Figure 3.7. Cylindrical Concrete Specimens Made with RPCC Aggregate.

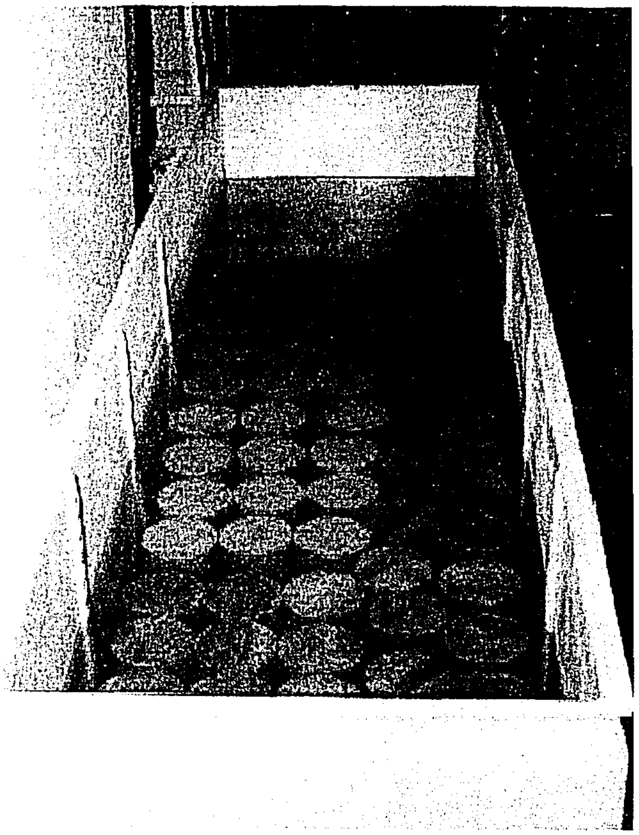

Figure 3.8. Curing Process of Cylindrical Concrete Specimens.

Table 3.5 contains the identification number description for the cylinders. Due to the quantity of planned batches, it was not possible to make all the concrete mix in one day, therefore it was decided that two batches would be made, one with natural and the other with recycled aggregate, and both with the same mixture designcharacteristic, i.e. water, cement and coarse aggregate contents

Table 3.5. Concrete Specimen Identification Numbers and Their Design Parameters.

Specimen Identification Number	Batch Identification Number	Maximum Size		Water-Cement Ratio	Age of testing	Number of specimens	Variation of f'c with respect to
		[in]	[mm]		[days]		
RACA-1-0.48-3	B1R-1-0.48	1	25.0	0.48	3	3	Age
RACA-1-0.48-7	B1R-1-0.48	1	25.0	0.48	7	3	Age
RACA-1-0.48-14	B1R-1-0.48	1	25.0	0.48	14	3	Age
RACA-1-0.48-28	B1R-1-0.48	1	25.0	0.48	28	3	Age
NACA-1-0.48-3	B1N-1-0.48	1	25.0	0.48	3	3	Age
NACA-1-0.48-7	B1N-1-0.48	1	25.0	0.48	7	3	Age
NACA-1-0.48-14	B1N-1-0.48	1	25.0	0.48	14	3	Age
NACA-1-0.48-28	B1N-1-0.48	1	25.0	0.48	28	3	Age
RACS-1-0.42-28	B2R-1-0.42	1	25.0	0.42	28	3	Slump
RACS-1-0.44-28	B2R-1-0.44	1	25.0	0.44	28	3	Slump
RACS-1-0.45-28	B2R-1-0.45	1	25.0	0.45	28	3	Slump
RACS-1-0.46-28	B2R-1-0.46	1	25.0	0.46	28	3	Slump
RACS-1-0.48-28	B2R-1-0.48	1	25.0	0.48	28	3	Slump
NACS-1-0.42-28	B2N-1-0.42	1	25.0	0.42	28	3	Slump
NACS-1-0.44-28	B2N-1-0.44	1	25.0	0.44	28	3	Slump
NACS-1-0.45-28	B2N-1-0.45	1	25.0	0.45	28	3	Slump
NACS-1-0.46-28	B2N-1-0.46	1	25.0	0.46	28	3	Slump
NACS-1-0.48-28	B2N-1-0.48	1	25.0	0.48	28	3	Slump
RACZ-1-0.44-28	B3R-1-0.44	1	25.0	0.44	28	3	Max. Size
RACZ-1-0.47-28	B3R-1-0.47	1	25.0	0.47	28	3	Max. Size
RACZ-1-0.50-28	B3R-1-0.50	1	25.0	0.50	28	3	Max. Size
RACZ-3/4-0.44-28	B3R-3/4-0.44	¾	19.0	0.44	28	3	Max. Size
RACZ-3/4-0.47-28	B3R-3/4-0.47	¾	19.0	0.47	28	3	Max. Size
RACZ-3/4-0.50-28	B3R-3/4-0.50	¾	19.0	0.50	28	3	Max. Size
RACZ-1/2-0.44-28	B3R-1/2-0.44	½	12.5	0.44	28	3	Max. Size
RACZ-1/2-0.47-28	B3R-1/2-0.47	½	12.5	0.47	28	3	Max. Size
RACZ-1/2-0.50-28	B3R-1/2-0.50	½	12.5	0.50	28	3	Max. Size
NACZ-1-0.44-28	B3N-1-0.44	1	25.0	0.44	28	3	Max. Size
NACZ-1-0.47-28	B3N-1-0.47	1	25.0	0.47	28	3	Max. Size
NACZ-1-0.50-28	B3N-1-0.50	1	25.0	0.50	28	3	Max. Size
NACZ-3/4-0.44-28	B3N-3/4-0.44	¾	19.0	0.44	28	3	Max. Size
NACZ-3/4-0.47-28	B3N-3/4-0.47	¾	19.0	0.47	28	3	Max. Size
NACZ-3/4-0.50-28	B3N-3/4-0.50	¾	19.0	0.50	28	3	Max. Size
NACZ-1/2-0.44-28	B3N-1/2-0.44	½	12.5	0.44	28	3	Max. Size
NACZ-1/2-0.47-28	B3N-1/2-0.47	½	12.5	0.47	28	3	Max. Size

3. 4. 4. Slump Tests.

A slump test was made to every batch to certify the concrete consistency. This procedure was made following ASTM C143 (19). The test equipment consisted in a steel rod and a cone of 12 inches (30.5 cm) height, 8 inches (20.3 cm) base diameter, and 4 inches (10.2 cm) top diameter. The test consisted in placing a layer of concrete inside the cone corresponding to approximately 1/3 of its volume. Next, the concrete was rodded by 25 uniformly distributed strokes using the steel rod. Filling and consolidation procedures were repeated two more times. Finally, the mold was raised and the freshly mixed concrete allowed set down freely. The vertical distance between the original and displaced position of the center of the top surface of the concrete was measured and reported as the slump of the concrete. An example of this test is shown in Figure 3.9.

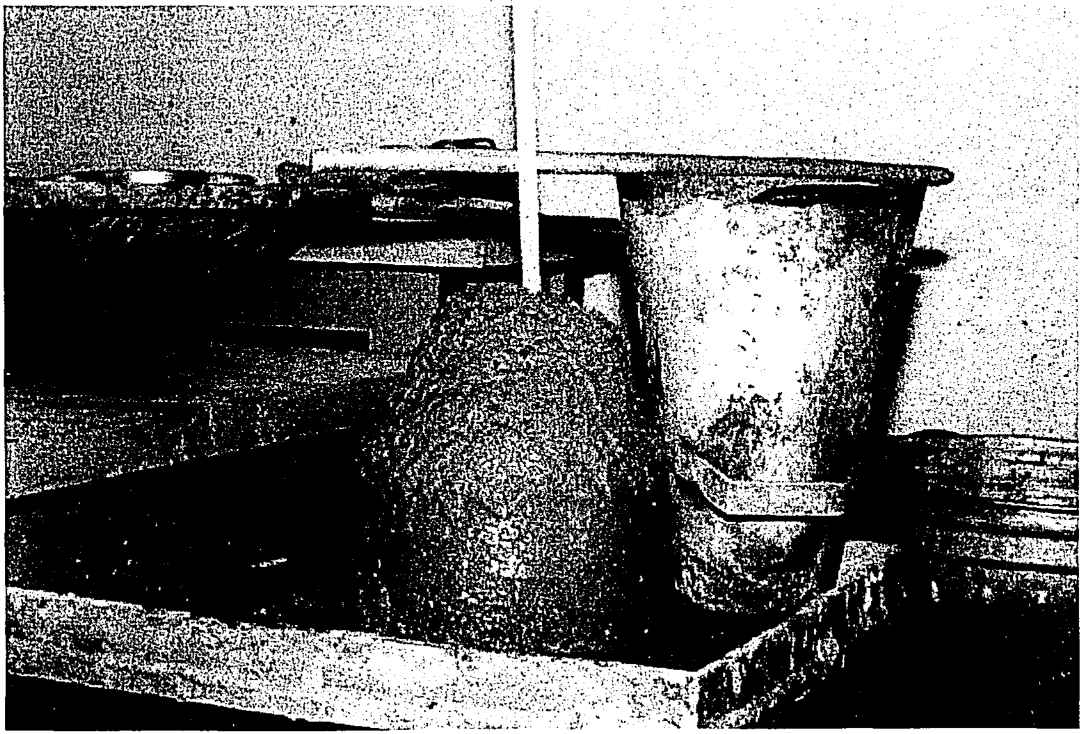

Figure 3.9. Slump Test.

3. 4. 5. Compression Tests.

The purpose of these tests was to determine the compressive strength of concrete specimens made with RPCC aggregate and to compare these values to those obtained for concrete specimens made with natural aggregate, having a comparable mixture design. The tests were made following the standard procedure described in ASTM C39 (21). The compression test consisted basically in applying a compressive axial load to a cylindrical concrete specimen continuously and without shock until failure occurred. Compressive strength (f'c) was calculated as the average value of the individual compressive strengths of the three specimens made from the same batch. The individual compressive strength was calculated by dividing the maximum load applied to a specimen during the test by the cross section area of that specimen. Figure 3.10 shows a typical compression test The specimens were made from the batches described in Table 3.5. All specimens were tested at 28 days of age, except those made from Batches 1N and 1RPCC

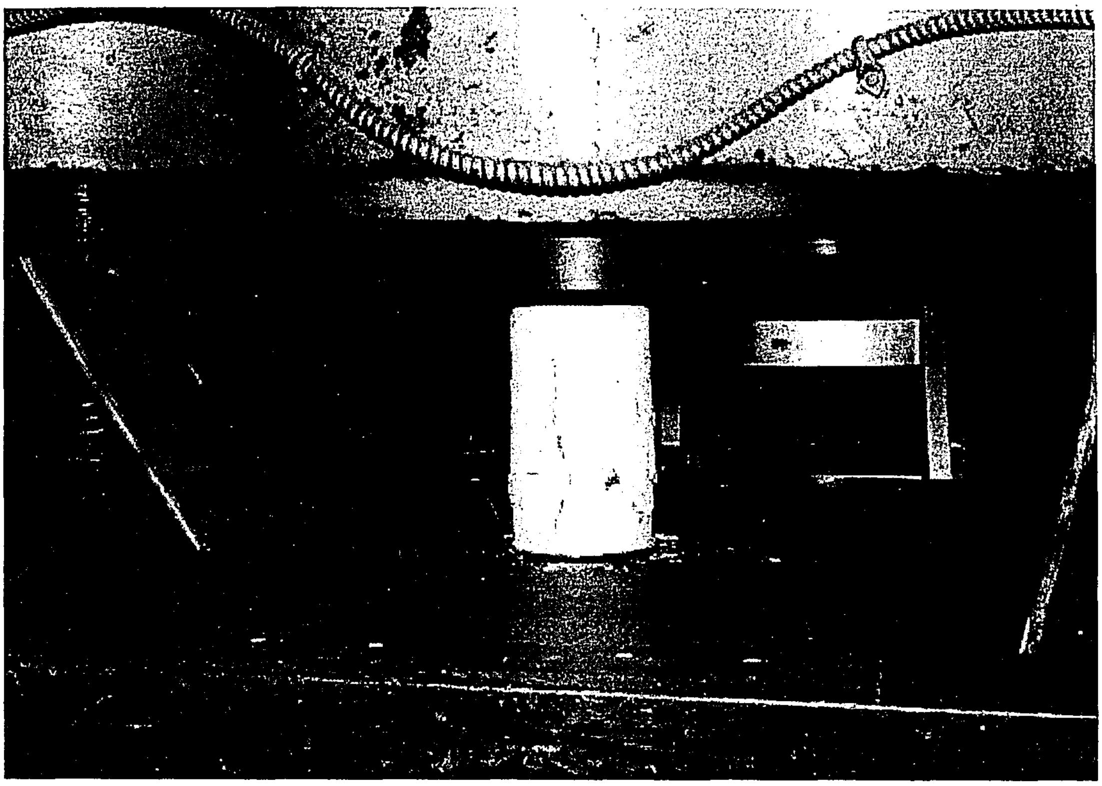

Figure 3.10. Compression Test.

3. 5. Shear Test.

Shear tests were made to RPCC material in order to determine its failure envelope and friction angle. The material tested consisted in coarse aggregate that satisfied the requirement imposed by AASTHO M57 (22). The material belonged to A-1-a group of classification according to AASTHO M145 (10), corresponding to coarse aggregate retained by sieve No.4. Its grading characteristics are presented in Figure 3.3 and Table 3.3.

The test equipment included a shear box designed at Lehigh University for shear testing purposes. It consisted of a square box of 4 ft^2 (0.372 m^2) of area and one foot height. The box was divided horizontally in two equal parts that allowed a relative displacement, as it can be seen in Figure 3.11. The shear box included a cover plate of 92 lb (0.409 kN) of weight.

The test method consisted in placing the recycled material in a confinement device (shear box) as it is shown in Figure 3.12. The material was then covered with the plate and a normal load was applied to the specimen. The load was maintained constant during the whole test. Next, shearing displacements were applied in a very slow rate and shear forces were measured. After reaching the failure the test was stopped. The failure occurred when the displacement reached between 10% and 20% of the original length of the shear box according to ASTM 3080 (23). The data obtained were plotted in a graphic containing Horizontal Force (shear force) versus Horizontal Displacement; the peak value in this graph corresponded to the shearing force at failure. The stresses were calculated as:

- Normal stress at failure, σ_f. $\sigma_f = \frac{NormalLoad}{Area}$ (3.7)
- Shear stress at failure, τ_f. $\tau_f = \frac{ShearingLoad}{Area}$ (3.8)

This procedure was repeated 4 times for axial loads of 500 lb (2.224 kN), 750 lb (3.336 kN), 1000 lb (4.448 kN), and 1250 lb (5.560 kN). The linear equation at failure for cohesionless soils has the form:

$$\tau_f = \sigma_f * \tan(\phi_f) \quad (3.9)$$

τ_f: Shear stress at failure.

σ_f: Normal stress at failure.

ϕ_f: friction angle.

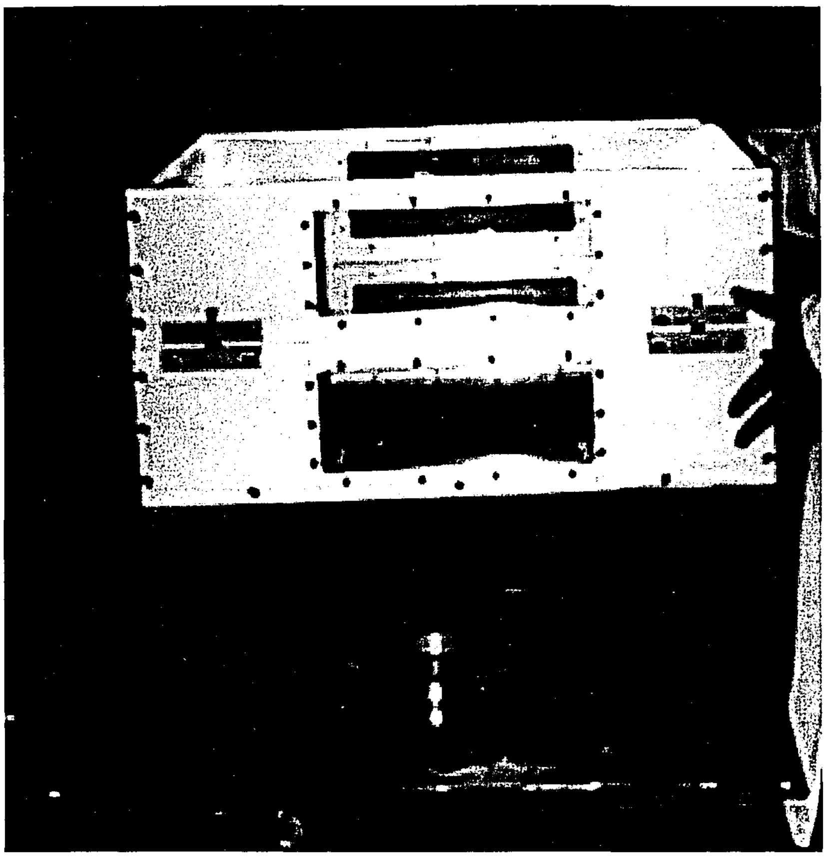

Figure 3.11. Shear Box.

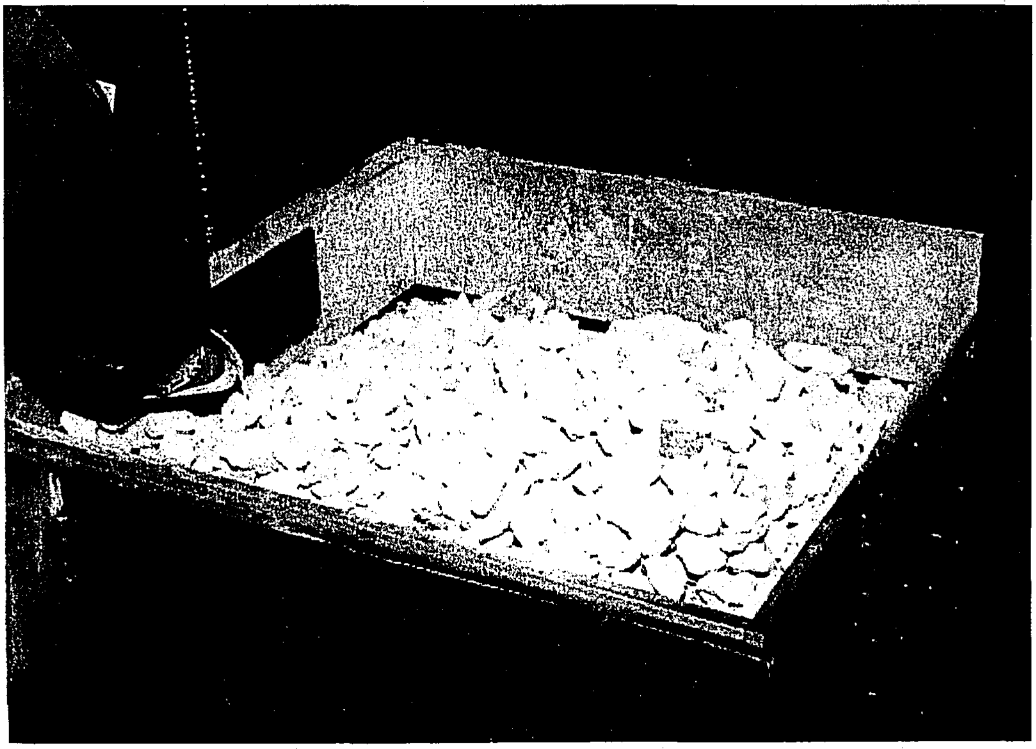

Figure 3.12. Placing RPCC Material for Testing.

Table 3.6. Range of Friction Angle for Soils. (24)

Soil Type	ϕ
• Gravel	35-50
• Mixtures of gravel and sand with fine-grained soils	30-40
• Sand	32-50
• Silt or silty sand	27-35
• Clays	20-30

This linear relationship between normal and shear stresses was obtained using the experiments data and a linear regression analysis. Some reference values (24) of friction angles for soils are:

3. 6. Comments.

1. In order to simplify calculations and eliminate errors caused by variation in moisture content of the material, the coarse aggregate was prewetted and then dried to a saturated surface-dry condition and placed in a covered container to keep it in this condition until it was used. Therefore, the content of water was modified and it corresponded to:

$$W_{CM} = W_C + CA + Ab_{CA} + Ab_{FA} - CA_{SSD} \tag{3.10}$$

Where:

W_{CM}: Modified quantity of water in lb per cu yard of freshly mixed concrete.

W_C: Quantity of water from mix design in lb. per cu yard of freshly mixed concrete.

CA: Coarse aggregate content in lb. per cu yard of freshly mixed concrete.

Ab_{CA}: Absorbed water by coarse aggregate in lb per cu yard of freshly mixed concrete.

Ab_{FA}: Absorbed water by fine aggregate in lb per cu yard of freshly mixed concrete.

CA_{SSD}: Coarse aggregate in saturated suface-dry condition in lb per cu yard of freshly mixed concrete.

2. It was intended to make the batches containing RPCC and natural aggregates and with similar characteristic the same day, such that the conditions of mix preparation were the same and did not affect the final results between the batches.

3. The cover of the shear box used for the shear test weighted 92 lb (0.409 kN). This value was added to the axial load applied to the specimen.

CHAPTER 4. RESULTS.

4. 1. Introduction.

Chapter 4 summarizes the data obtained in this study and their analysis. The chapter is divided in three parts. The first part contains the results from the specific gravity and absorption test performed on RPCC and natural material. The second part deals with the mixture design of the concrete plus the results from tests made to freshly mixed and hardened Portland Cement Concrete (PCC), including slump and compression tests. The last part of the chapter contains the results from the application of shear tests to RPCC material.

The tests, results, and analysis presented on this chapter had the aim of describing the behavior of concrete made from Reclaimed Portland Cement Concrete in general and comparing it to concrete made from conventional aggregate. The size of the sample and the distribution of the results permits the use of the obtained models as a general representation of the performance of the concrete specified in this study and it is not intended to be applied to other kinds of concrete.

4. 2 Material Properties

In this section, physical properties (specific gravity and absorption) of the RPCC aggregate and natural aggregate were determined with the objective of using them in the mixture design process.

4. 2. 1. Specific Gravity and Absorption

The test methods for specific gravity and absorption (18) were applied to two samples: a RPCC and a natural coarse aggregate samples, each one with a saturated-surface-dry weight of 9.20 lb (4.17 kg.). The results are summarized in Table 4.1. From Table 4.1, the different properties are apparent. The specific gravity value for RPCC aggregate was a 7.9% lower than that of natural aggregate. On the other hand, the absorption for RPCC material was 3.6 times the value obtained for natural aggregate.

Table 4.1. Specific Gravity and Absorption Results.

	RPCC Aggregate	**Natural Aggregate**
Oven dry weight (A), lb (kg).	8.85 (4.01)	9.10 (4.13)
Saturated-surface-dry weight (B), lb (kg).	9.20 (4.17)	9.20 (4.17)
Saturated weight in water (C), lb (kg).	5.40 (2.45)	5.60 (2.54)
Bulk Specific Gravity	2.33	2.53
Bulk Specific Gravity (saturated-surface-dry), (SSD)	2.42	2.56
Apparent Specific Gravity	2.57	2.60
Absorption, %	4.0	1.1

Note: Bulk specific gravity = A/(B-C).
Bulk specific gravity (SSD) = B/(B-C).
Apparent specific gravity = A/(A-C).
Absorption = [(B-A)/A]*100.

4. 2. 2. Sieve Analysis of Fine Aggregate.

Sieve analysis was conducted on the fine natural aggregate following ASTM C136 (16) and ASTM C702 (17) standard specifications. Four samples were analyzed and the average results are presented in Table 4.2 and Figure 4.1. The sieve analysis ensured that the fine aggregate satisfied ASTM C33 (14) requirements.

4. 3. Portland Cement Concrete (PCC).

Portland cement concrete was made from RPCC as well as natural aggregate with the purpose of study the behavior of freshly mixed and hardened concrete. Here, the concrete mixture designs and the results for slump and compression tests are presented.

Table 4.2.Sieve Analysis of Fine Aggregate.

Sieve Size		Fine Aggregate	ASTM C33 Requirements (14)
No.	mm.	% passing by weight	% passing by weight
3/8"	9.50	100	100
4	4.75	97	95-100
8	2.36	81	80-100
30	0.60	29	25-60
50	0.30	10	5-30
100	0.15	3	0-10

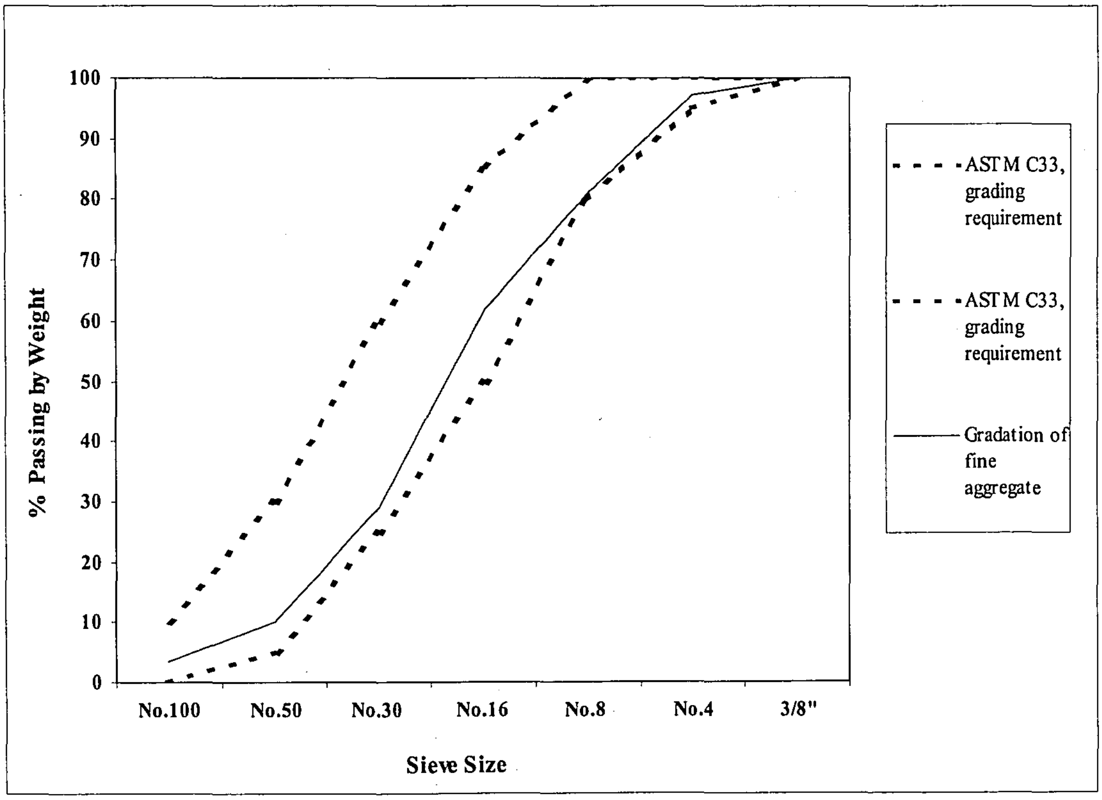

Figure 4.1. Sieve Analysis of Natural Fine Aggregate.

4. 3. 1. Mixture Design.

A total of 30 batches were designed based on the Absolute Volume Method (8), 15 made with recycled and 15 with natural coarse aggregate. The specific gravity and absorption values obtained in Table 4.1 were included in the design process. It can be seen in Table 4.3 that the content of fine aggregate constituted the only difference between batches with the same maximum size of coarse aggregate and water cement ratio, made with RPCC and natural aggregate. On the average, the fine aggregate content was 14.2% more in batches made with natural aggregate. The content of fine aggregate was calculated according to equations 3.5 and 3.6. From these equations, it can be seen that the larger the specific gravity, the larger the fine aggregate volume and fine aggregate content. Therefore, the batches made with natural aggregate (bigger specific gravity) needed more fine aggregate content as shown in Table 4.3.

The actual water cement ratio of some of the batches differed from those specified in Chapter 3, Table 3.4, because the workability of the concrete was poor or the measured slump did meet specification (19). The modified batches are shown in Table 4.4.

Table 4.3. Batch Identification Numbers and Mixture Design.

No	Batch Identification Number	Water-Cement Ratio	Maximum Size	Quantity of Water	Cement Content	Coarse Aggregate Content	Fine Aggregate Content
			in (mm.)	lb*(kg**)	lb*(kg**)	lb*(kg**)	lb*(kg**)
1	**B1R-1-0.48**	0.48	1 (25.0)	335 (198.8)	678 (402.3)	1782 (1057.3)	976 (579.1)
2	**B1N-1-0.48**	0.48	1 (25.0)	335 (198.8)	678 (402.3)	1782 (1057.3)	1136 (674.0)
3	**B2R-1-0.42**	0.42	1 (25.0)	285 (169.1)	678 (402.3)	1782 (1057.3)	1108 (657.4)
4	**B2R-1-0.44**	0.44	1 (25.0)	295 (175.0)	678 (402.3)	1782 (1057.3)	1082 (642.0)
5	**B2R-1-0.45**	0.45	1 (25.0)	305 (181.0)	678 (402.3)	1782 (1057.3)	1056 (626.5)
6	**B2R-1-0.46**	0.46	1 (25.0)	315 (186.9)	678 (402.3)	1782 (1057.3)	1029 (610.5)
7	**B2R-1-0.48**	0.48	1 (25.0)	325 (192.8)	678 (402.3)	1782 (1057.3)	1003 (595.1)
8	**B2N-1-0.42**	0.42	1 (25.0)	285 (169.1)	678 (402.3)	1782 (1057.3)	1268 (752.3)
9	**B2N-1-0.44**	0.44	1 (25.0)	295 (175.0)	678 (402.3)	1782 (1057.3)	1242 (736.9)
10	**B2N-1-0.45**	0.45	1 (25.0)	305 (181.0)	678 (402.3)	1782 (1057.3)	1215 (720.8)
11	**B2N-1-0.46**	0.46	1 (25.0)	315 (181.0)	678 (402.3)	1782 (1057.3)	1189 (705.4)
12	**B2N-1-0.48**	0.48	1 (25.0)	325 (186.9)	678 (402.3)	1782 (1057.3)	1162 (689.4)
13	**B3R-1-0.44**	0.44	1 (25.0)	300 (178.0)	682 (404.6)	1782 (1057.3)	1065 (631.8)
14	**B3R-1-0.47**	0.47	1 (25.0)	320 (189.9)	682 (404.6)	1782 (1057.3)	1011 (599.8)
15	**B3R-1-0.50**	0.50	1 (25.0)	341 (202.3)	682 (404.6)	1782 (1057.3)	957 (567.8)
16	**B3R-3/4-0.44**	0.44	¾ (19.0)	315 (186.9)	716 (424.8)	1647 (977.1)	1150 (682.3)

Table 4. 3. Batch Identification Numbers and Mixture Design. (Continuation)

No	Batch Identification Number	Water-Cement Ratio	Maximum Size	Quantity of Water	Cement Content	Coarse Aggregate Content	Fine Aggregate Content
			in. (mm.)	lb*(kg**)	lb*(kg**)	lb*(kg**)	lb*(kg**)
17	**B3R-3/4-0.47**	0.47	¾ (19.0)	336 (199.3)	716 (424.8)	1647 (977.1)	1093 (648.5)
18	**B3R-3/4-0.50**	0.50	¾ (19.0)	358 (212.4)	716 (424.8)	1647 (977.1)	1037 (615.2)
19	**B3R-1/2-0.44**	0.44	½ (19.0)	335 (198.7)	761 (451.5)	1458 (865.0)	1273 (755.2)
20	**B3R-1/2-0.47**	0.47	½ (12.5)	358 (212.4)	761 (451.5)	1458 (865.0)	1213 (719.6)
21	**B3R-1/2-0.50**	0.50	½ (12.5)	381 (226.0)	761 (451.5)	1458 (865.0)	1153 (684.0)
22	**B3N-1-0.44**	0.44	1 (25.0)	300 (178.0)	682 (404.6)	1782 (1057.3)	1225 (726.8)
23	**B3N-1-0.47**	0.47	1 (25.0)	320 (189.8)	682 (404.6)	1782 (1057.3)	1171 (694.7)
24	**B3N-1-0.50**	0.50	1 (25.0)	341 (202.3)	682 (404.6)	1782 (1057.3)	1117 (662.7)
25	**B3N-3/4-0.44**	0.44	¾ (19.0)	315 (186.9)	716 (424.8)	1647 (977.1)	1298 (770.1)
26	**B3N-3/4-0.47**	0.47	¾ (19.0)	336 (212.4)	716 (424.8)	1647 (977.1)	1241 (736.3)
27	**B3N-3/4-0.50**	0.50	¾ (12.5)	358 (198.7)	716 (424.8)	1647 (977.1)	1184 (702.4)
28	**B3N-1/2-0.44**	0.44	½ (12.5)	335 (212.4)	761 (451.5)	1458 (865.0)	1404 (833.0)
29	**B3N-1/2-0.47**	0.47	½ (12.5)	358 (198.7)	761 (451.5)	1458 (865.0)	1344 (797.4)
30	**B3N-1/2-0.50**	0.50	½ (12.5)	381 (226.0)	761 (451.5)	1458 (865.0)	1283 (761.2)

---

* : lb. per cu yard of freshly mixed concrete.

** : kg. per cu meter of freshly mixed concrete.

Table 4.4. Modified Batches

No	Original Batch Identification Number	Modified Batch Identification Number	Original Water Cement Ratio	Modified Water Cement Ratio
1	B1R-1-0.48	**B1R-1-0.49**	0.48	0.49
2	B1N-1-0.48	**B1N-1-0.49**	0.48	0.49
3	B2R-1-0.42	**B2R-1-0.43**	0.42	0.43
4	B2R-1-0.45	**B2R-1-0.46**	0.45	0.46
5	B2R-1-0.46	**B2R-1-0.47**	0.46	0.47
6	-	**B2R-1-0.49**	-	0.49
7	B2N-1-0.44	**B2N-1-0.45**	0.44	0.45
8	B2N-1-0.45	**B2N-1-0.49**	0.45	0.49
9	B2N-1-0.46	**B2N-1-0.51**	0.46	0.51

4. 3. 2. Slump Tests

Slump tests were conducted on 12 different batches. The results from these tests are presented in Table 4.5 and Figure 4.2. Figure 4.2 presents the slump test results as a function of the water cement ratio (WCR). The shape of the curve used to model the slump-WCR relationship was based on a more simple approach of Popovics' formula (25).

Table 4.5. Slump Test Results for Portland Cement Concrete Made from RPCC and Natural Aggregates.

Number	Batch Identification Number	Maximum Size		Water Cement Ratio	Slump	
		[in]	[cm]		[in]	[cm]
1	B2R-1-0.43	1	2.5	0.43	1.5	3.8
2	B2R-1-0.44	1	2.5	0.44	2.1	5.3
3	B2R-1-0.46	1	2.5	0.46	4.0	10.2
4	B2R-1-0.47	1	2.5	0.47	6.5	16.5
5	B2R-1-0.48	1	2.5	0.48	1.0	2.5
6	B2R-1-0.49	1	2.5	0.49	5.0	12.7
7	B2N-1-0.42	1	2.5	0.42	0.5	1.3
8	B2N-1-0.45	1	2.5	0.45	1.5	3.8
9	B2N-1-0.48	1	2.5	0.48	3.0	7.6
10	B2N-1-0.49	1	2.5	0.49	3.5	8.9
11	B2N-1-0.51	1	2.5	0.51	5.0	12.7

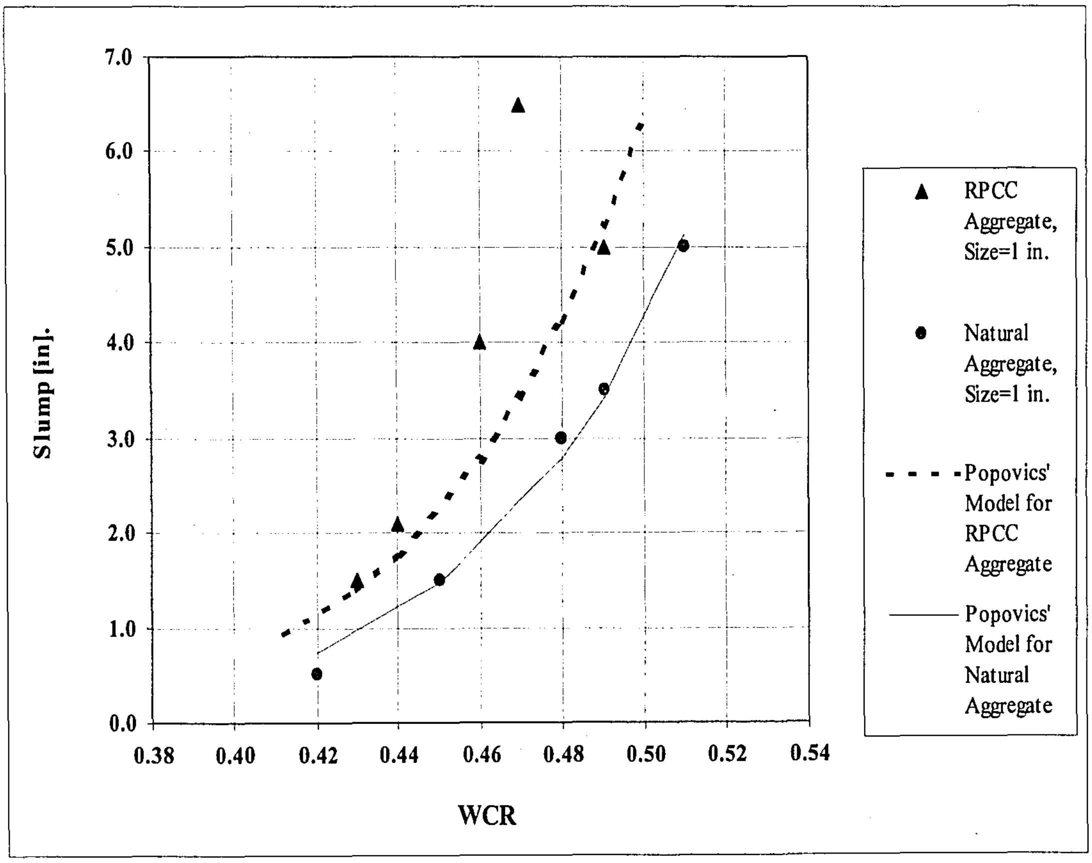

Figure 4.2. Slump - Water Cement Ratio Relationship.

The shape's curve was expressed as follows:

$$S = 4 * \left(\frac{WCR}{A_s} \right)^{10} \tag{4.1}$$

S: Slump, [in].

WCR: Water Cement Ratio.

A_s: Constant.

The least squares method was applied to the data to fit them to equation 4.1, the obtained expressions are:

- Slump for batches with RPCC coarse aggregate:

$$S_{RPCC} = 4 * \left(\frac{WCR}{0.4773} \right)^{10} \tag{4.2}$$

- Slump for batches with Natural coarse aggregate:

$$S_{Nat} = 4 * \left(\frac{WCR}{0.4975} \right)^{10} \tag{4.3}$$

Two observations can be made from Figure 4.2:

1. The data distribution from batches made with natural coarse aggregate fits better its curve; on the contrary, the data from batches made with RPCC coarse aggregate shows a more irregular distribution. This may be because batches with RPCC aggregate were more sensitive to the water cement ratio, and therefore more sensitive to the quantity of water (cement content remaining constant).

2. For a given water cement ratio (WCR), the evaluated slump was in average 1.8 inches (4.6 cm) higher in equation 4.2 than that of 4.3. This demonstrates a higher sensitivity to the quantity of water for batches made with RPCC aggregate.

For a given WCR, mixtures made with recycled aggregate were easier to cast, compact, and finish, they also showed a higher flowability compared to mixtures made with conventional aggregate.

The finding mentioned above suggests that for a specified slump, concrete made with recycled concrete may need lower quantity of water than concrete made with natural aggregate without losing flowability and plasticity. A lower demand of water would help improve the compressive strength of the hardened concrete.

4. 3. 3. Compression Tests.

The objective of the compression tests was to determine the compressive strength behavior of the concrete made with RPCC aggregate ($f'c_{RPCC}$) and then compare it to the compressive strength of concrete with the same characteristics but made with natural aggregate ($f'c_{Nat}$). For this purpose, several batches were prepared varying parameters like water cement ratio and maximum size of the aggregate, and cylindrical concrete specimens were made from these mixtures. The specimens were tested in compression in order to determine the relationship between compressive strength and age of the concrete, water cement ratio, slump, and maximum size of the aggregate.

Table 4.6. Compressive Strength for Concrete Specimens at Different Ages.

Age	Specimens Identification number	Compressive Strength. $f'c_{RPCC}$		Specimens Identification number	Compressive Strength. $f'c_{Nat}$		$\Delta f'c$
[days]		[psi]	[MPa]		[psi]	[MPa]	[%]
3	RACA-1-0.49-3	2390*	16.4	NACA-1-0.49-3	2920	20.1	18.1
7	RACA-1-0.49-7	3110*	21.4	NACA-1-0.49-7	3430	23.6	9.3
14	RACA-1-0.49-14	3520*	24.3	NACA-1-0.49-14	3870	26.7	9.9
28	RACA-1-0.49-28	4120	28.4	NACA-1-0.49-28	4510*	31.1	8.6

Note: $\Delta f'c = 100 * \underline{(f'c_{Nat} - 'c_{RPCC})} / f'c_{Nat.}$

$\frac{\text{Water}}{\text{Cement}} = 0.49$

*: average of two specimens according to ASTM C 670 –96

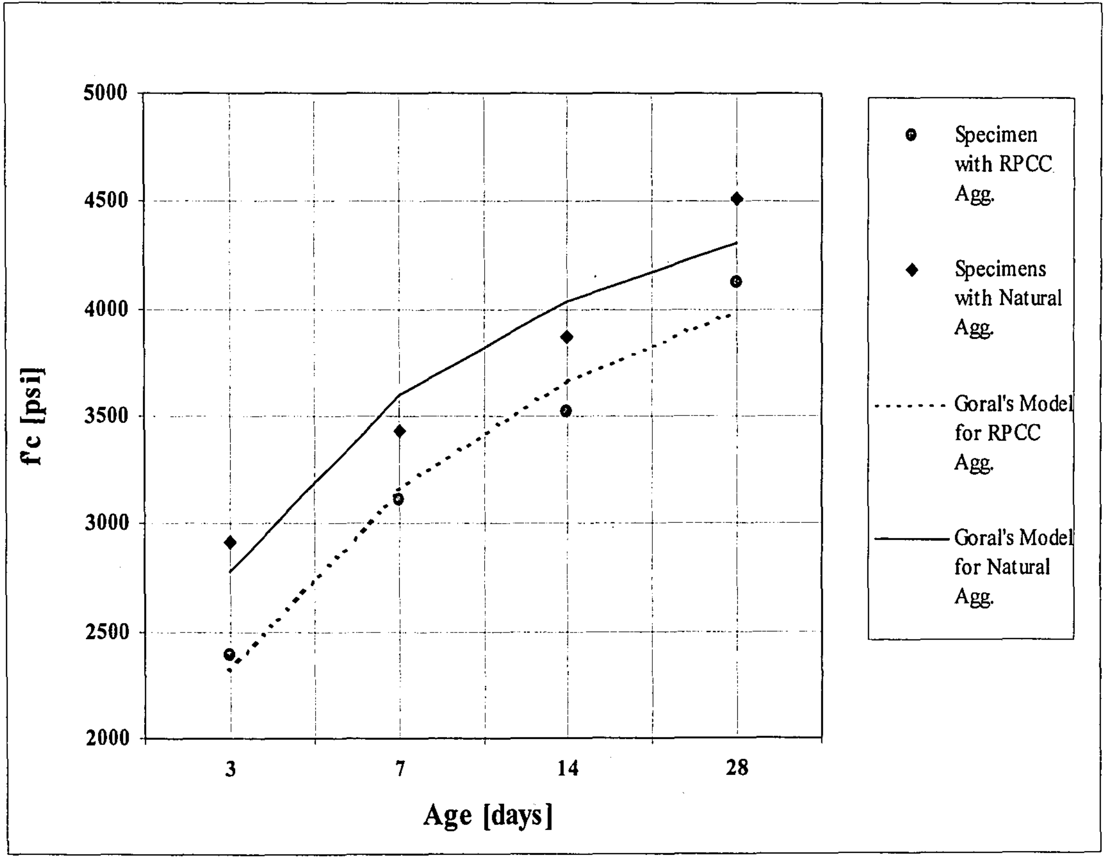

Figure 4.3. Compressive Strength Versus Age.

4. 3. 3. 1. Compressive Strength Versus Age.

A total of 24 specimens were tested at ages of 3, 7, 14, and 28 days. All specimens were made on the same date. Table 4.6 contains the tests data and Figure 4.3. shows a graphic representation of the results. From Table 4.6 and Figure 4.3 it can be seen that, the behavior of compressive strength (f'c) for both aggregates was very similar. The curve from the RPCC material is below the natural material. At 3 days of age occurred the largest difference of f'c between the results from natural and RPCC aggregate specimens, where f'c from specimens made with RPCC aggregate was 18.1% smaller than that of specimens made with natural aggregate, as it is shown in Table 4.6. This difference dropped to 8.6% for the 28 days specimens. Although this difference is important, it is close to the maximum allowed difference among three individual compression tests given by ASTM 670 (26) specification, which is 7.8%.

There were cases where the difference between the maximum and minimum values of f'c was larger than 7.8% (limit established for ASTM 670-96), for a three-specimen set made from the same concrete. In those cases, the f'c value was estimated as the average of the two cylinders with the closer f'c (values with * in Table 4.6).

The data were modeled using Goral's equation (25), and the fitted curves are shown in Figure 4.3. Goral's expression has the form:

$$f'c_a = \frac{t}{A_a * t + B_a} \qquad (4.4)$$

f'c: Compressive strength at t age, [psi].

t: Age, [days].

A_a and B_a: Constants.

The least squares method was applied to the data to fit them to equation 4.4, the obtained expressions are:

- f'c for concrete with RPCC coarse aggregate:

$$f'c_{aRPCC} = \frac{t}{2.29*10^{-4}*t+6.12*10^{-4}} \tag{4.5}$$

- f'c for concrete with Natural coarse aggregate:

$$f'c_{aNat} = \frac{t}{2.17*10^{-4}*t+4.30*10^{-4}} \tag{4.6}$$

According to these models, when t approaches to ∞, $f'c_{aRPCC}$ is approximately 4610 psi (31.8 MPa), and $f'c_{aNat}$ is approximately 4370 psi (30.1 MPa), and the difference between them ($\Delta f'c$) approaches to 5.2%. Therefore, the final strength would be closer than the results at 28 days of age, and the difference would approach a reasonable value.

4. 3. 3. 2. Compressive Strength Versus Water Cement Ratio.

Water cement ratio is a variable that has high influence in the concrete performance. In order to quantify this influence, a total of 30 specimens were made (15 from RPCC and 15 from natural material) with different water cement ratios, the quantity of water was varied and the cement content was maintained constant. Table 4.7 and Figure 4.4 show the results from the compression tests.

The individual values of compressive strength for specimens made with RPCC aggregate had a greater scatter than the corresponding values for specimens made with natural aggregate. This could indicate a bigger sensitivity of the concrete made from recycled aggregate to the quantity of water.

To model the data, Abrams' formula (25) was used:

$$f'c_w = A_w * 10^{-(WCR*B_w)} \tag{4.7}$$

$f'c_w$: Compressive strength, [psi].

WCR: Water cement ratio

A_w and B_w: Constants.

The least squares method was applied to the data to fit them to equation 4.7. The obtained expressions are:

- $f'c_w$ for concrete with RPCC coarse aggregate ($f'c_{wRPCC}$):

$$f'c_{wRPCC} = 31362.2 * 10^{-(WCR*2.051)} \tag{4.8}$$

- $f'c_w$ for concrete with Natural coarse aggregate ($f'c_{wNat}$):

$$f'c_{wNat} = 11165.1 * 10^{-(WCR*0.827)} \tag{4.9}$$

Both curves are shown in Figure 4.4. All data from specimens made from natural aggregate were considered to perform the curve fit. For the case of specimens made with recycled aggregate only four out of the six results were considered. The points corresponding to WCR = 0.48 and 0.49 were not considered, because they were far from the rest of the results and produced an important distortion in the modeling of the data.

From Figure 4.4, the f’c_{RPCC} curve was below the f’c_{Nat} curve in the interval 0.40-0.52 of WCR. It can also be observed that the compressive strength decreases with WCR for both concretes, but more rapidly for the recycled aggregate case. The observations confirmed two well-known concrete characteristics: first, concrete made with recycled aggregate has a lower compressive strength than conventional concrete; second, the f’c decreases when the water cement ratio increases.

Table 4.7. Compressive Strength of Concrete Specimens with Different Water Cement Ratio.

No.	Specimens Identification number	Water Cement Ratio	Compressive Strength. f’c		Age	Observations
			[psi]	[MPa]	[days]	
1	RACA-1-0.43-28	0.43	4010	27.6	28	Max. size agg. = 1in *: Average of two specimens according to ASTM C 670 –96 ^{n}: points not included in modeling process.
2	RACA-1-0.44-28	0.44	4040*	27.9	28	
3	RACA-1-0.46-28	0.46	3670*	25.3	28	
4	RACA-1-0.47-28	0.47	3300*	22.8	28	
5	RACA-1-0.48-28	0.48	4430^{n}	30.5	28	
6	RACA-1-0.49-28	0.49	4120^{n}	28.4	28	
7	NACA-1-0.42-28	0.42	5130*	35.4	28	
8	NACA-1-0.45-28	0.45	4480	30.9	28	
9	NACA-1-0.48-28	0.48	4630*	31.9	28	
10	NACA-1-0.49-28	0.49	4490	31.0	28	
11	NACA-1-0.51-28	0.51	4150	28.6	28	

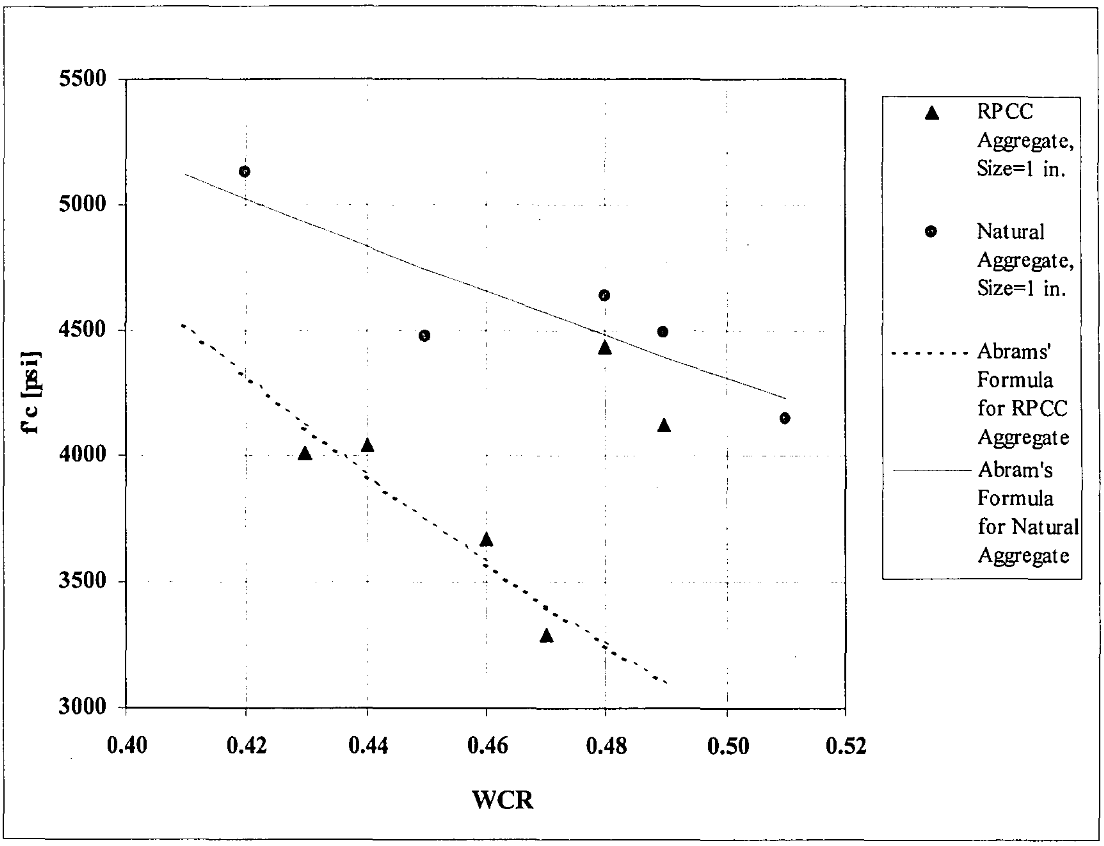

Figure 4.4. Compressive Strength Versus Water Cement Ratio.

If equations 4.8 and 4.9 were extrapolated, they would intersect at WCR =0.366 and f'c= 5560 psi (38.3 MPa), and below that WCR compressive strength for concrete made with recycled aggregate would be greater than the conventional concrete strength, but no data were obtained in that range of WCR to substantiate this hypothesis. In practice, WCR specified for normal concrete (not high strength concrete) are usually greater than 0.4. For a specified compressive strength it is possible to find the relation between the WCR for RPCC concrete (WCR_{RPCC}) and WCR for Natural concrete (WCR_{Nat}) by using 4.8 and 4.9. The final expression is:

$$WCR_{RPCC} = 0.2187 + WCR_{nat} * 0.4030 \qquad (4.10)$$

and, in general terms:

$$WCR_{RPCC} = \frac{\left(\log(\frac{A_{wRPCC}}{A_{wNat}}) + WCR_{nat} * B_{Wnat} \right)}{B_{wRPCC}} \quad (4.11)$$

Hence, for a specified WCR and f'c of a desired Portland cement concrete with conventional aggregate, it would be possible to obtain the equivalent WCR needed when RPCC coarse aggregate is used. Moreover, using equations 4.10 and 4.3 it is possible to determine the slump. Taking $WCR_{nat} = 0.48$ as example, the corresponding f'c would be 4480 psi (30.9 MPa) from equation 4.9 and the slump 2.8 in (7.1 cm.) from equation 4.3. The equivalent WCR_{RPCC} would be 0.41 from equation 4.10. Applying equation 4.2, the slump associated to recycled concrete should be 1.5 in (3.8 cm). The purpose of this example is to show that it would be possible to establish a relation between the use of natural and recycled aggregate, and that it would be possible to achieve the same level of compressive strength by changing parameters like WCR and Slump in the mixture design.

4. 3. 3. 3. Compressive Strength Versus Slump.

The specimens used for this part of the study were made from the batches in Table 4.5. The obtained slump for each individual batch was associated to the cylindrical concrete specimens made from that batch. The specimens were tested in compression at 28 days of age. The results as a function of the slump are summarized in Table 4.8 and Figure 4.5.

Table 4.8. Compressive Strength for Concrete Specimens with Different Slump.

No.	Specimens Identification number	Slump		Compressive Strength. $f'c_{RPCC}$		Age	Observations
		[in]	[cm]	[psi]	[MPa]	[days]	
1	RACA-1-0.48-28	1	2.5	4430	30.5	28	Max. size agg. = 1in *: average of two specimens according to ASTM C 670 -96
2	RACA-1-0.43-28	1.5	3.8	4010	27.6	28	
3	RACA-1-0.44-28	2.1	5.3	4040*	27.9	28	
4	RACA-1-0.46-28	4.0	10.2	3670*	21.2	28	
5	RACA-1-0.49-28	5.0	12.7	4120	28.4	28	
6	RACA-1-0.47-28	6.5	16.5	3300*	22.7	28	
7	NACA-1-0.42-28	0.5	1.3	5130*	35.4	28	
8	NACA-1-0.45-28	1.5	3.8	4480	30.9	28	
9	NACA-1-0.48-28	3.0	7.6	4630*	31.9	28	
10	NACA-1-0.49-28	3.5	8.9	4490	31.0	28	
11	NACA-1-0.51-28	5.0	12.7	4150	28.6	28	

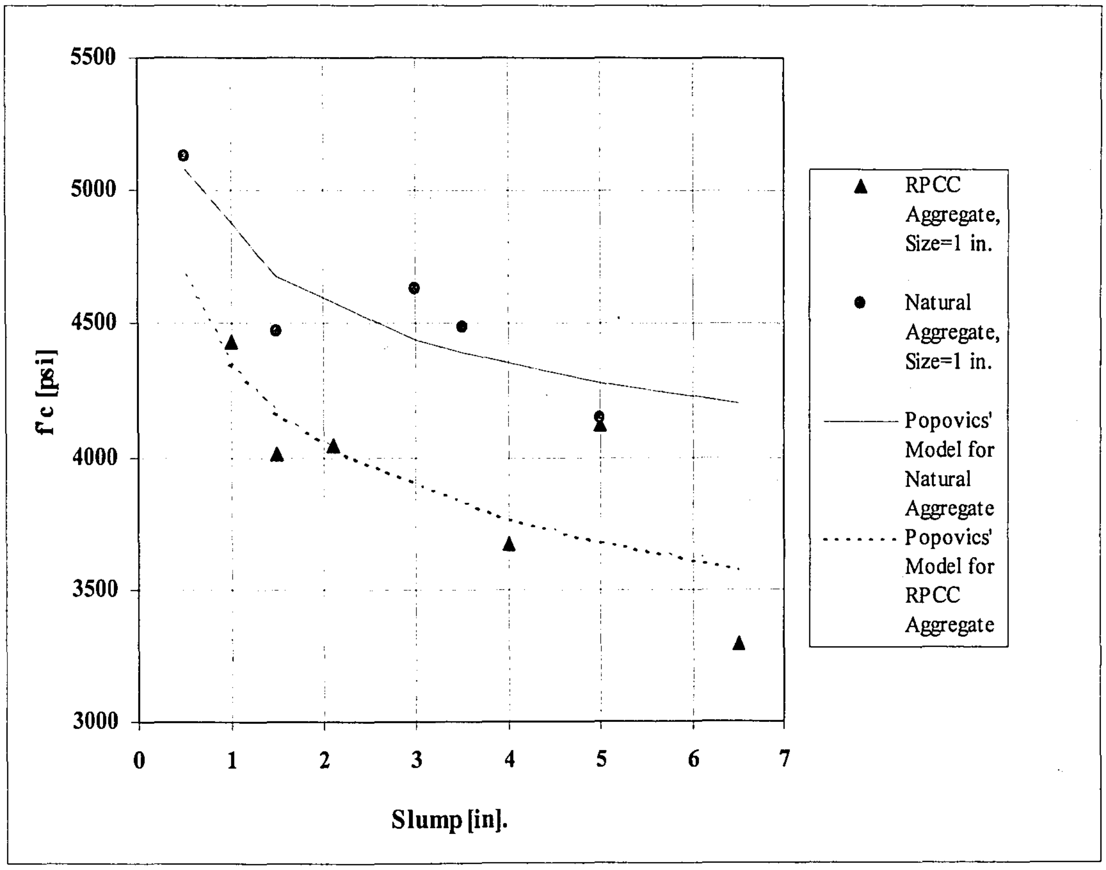

Figure 4.5. Compressive Strength Versus Slump.

The results obtained agreed with the previous obtained relationships. It was confirmed that slump increased as WCR increased and f'c decreased with increasing WCR, therefore it was expected that f'c would be a decreasing function of slump. The results obtained and shown in Table 4.8 and Figure 4.5 confirm this trend.

Popovics' formula (25) was used to develop a relationship for slump and compression strength.

$$f'c_{ss} = \frac{A_{ss}}{\left(\frac{S}{4}\right)^{0.1}} - B_{ss} \tag{4.12}$$

f'c$_{ss}$: Compressive strength, [psi].

S: Slump, [in].

A$_{ss}$ and B$_{ss}$: Constants.

The least square method was applied to the data to fit them to equation 4.12. The obtained expressions are:

- f'c$_{ss}$ for concrete with RPCC coarse aggregate (f'c$_{ssRPCC}$):

$$f'c_{ssRPCC} = \frac{3933.4}{\left(\frac{S}{4}\right)^{0.1}} - 167.87 \tag{4.13}$$

- f'c$_{ss}$ for concrete with Natural coarse aggregate (f'c$_{ssNat}$):

$$f'c_{ssNat} = \frac{3153.7}{\left(\frac{S}{4}\right)^{0.1}} + 1195.6 \tag{4.14}$$

The compressive strength behavior for both concretes was similar. Comparing f'c$_{ssRPCC}$ and f'c$_{ssNat}$ curves, in both cases f'c had its maximum value when S→0 and f'c had its minimum value when S→ 12 in (30.5 cm), maximum slump cone. Taking the f'c versus WCR relationships and a given WCR = 0.46, the compressive strengths given by equations 4.8 and 4.9 would be $f'c_{wRPCC}$ =3570 psi (24.6 MPa) and $f'c_{wNat}$ =4650 psi (32.1 MPa), respectively. Therefore, the difference in compressive strength would be $\Delta f'c_w = 23.2\%$[t]. Now, taking the f'c versus slump relationships and a given slump of 1.6 inches (4.1 cm) the compressive strength given by the equations 4.13 and 4.14 would be $f'c_{ssRPCC}$ =4143 psi (28.6 MPa) and $f'c_{ssNat}$ =4650 psi (32.1 MPa), respectively. Therefore, in this case, the difference in compressive strength would be $\Delta f'c_{ss} = 10.9\%$[tt]. The difference in compressive strength was larger using the models for f'c versus WCR. Usually, models of f'c as a function of slump also included other parameter, like content of cement and finesse modulus of the aggregate (25); then it could be that the slump models shown here were too simple and they could underestimate the compressive strength.

4. 3. 3. 4. *Compressive Strength Versus Maximum Size of the Aggregate.*

Maximum size of the aggregate is another variable in compressive strength of concrete. It is known that the strength of comparable concretes with identical water cement ratios usually increase as the maximum size of the aggregate (MSA) decreases, the explanation for this is that the bond of the cement paste to the

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[t] : $\Delta f'c_w = \dfrac{(f'c_{wNat} - f'c_{wRPCC})}{f'c_{wNat}}$

[tt] : $\Delta f'c_{ss} = \dfrac{(f'c_{ssNat} - f'c_{ssRPCC})}{f'c_{ssNat}}$

aggregate particles of large sizes is weaker than the bond to smaller sizes because of the smaller surface of the former. Table 4.9 contains the results of compression test applied to concrete specimens made from RPCC and Natural aggregate, with different maximum size of the aggregate and water cement ratio. The maximum sizes used were: ½ in (1.3 cm), ¾ in (1.9 cm), and 1 in (2.5 cm), and the water cement ratios were: 0.44, 0.47, and 0.50. Figure 4.6 displays the final results.

From Figure 4.6 for each concrete, the highest compressive strength values were those obtained from specimens with the maximum size of ½ inch (1.3 cm) and WCR of 0.44, and the weakest specimens were those with the maximum size of 1 inch (2.5 cm) and WCR of 0.47 and 0.50. In general, Figure 4.6 shows similar trend for the concrete made with reclaimed aggregate with respect to the concrete made with natural aggregate as in previous cases, (i.e. the compressive strength of specimens made with RPCC aggregate under that of specimens made with RPCC aggregate). Some exceptions were:

Table 4.9. Compressive Strength for Concrete Specimens Versus Different Maximum Size of the Aggregate.

No.	Specimens Identification number	Water Cement Ratio	Max. Size		Compressive Strength. f'c		Age	Observations
			[in]	[cm]	[psi]	[MPa]		
1	RACZ-1/2-0.44-28	0.44	½	1.3	4350	30.0	28	*: Average of two specimens according to ASTM C 670 – 96
2	RACZ-1/2-0.47-28	0.47	½	1.3	4480	30.9	28	
3	RACZ-1/2-0.50-28	0.50	½	1.3	3390	23.4	28	
4	RACZ-3/4-0.44-28	0.44	¾	1.9	4120*	28.4	28	
5	RACZ-3/4-0.47-28	0.47	¾	1.9	3890	26.8	28	
6	RACZ-3/4-0.50-28	0.50	¾	1.9	3890	26.8	28	
7	RACZ-1-0.44-28	0.44	1	2.5	3910	37.0	28	
8	RACZ-1-0.47-28	0.47	1	2.5	3300	22.8	28	
9	RACZ-1-0.50-28	0.50	1	2.5	3300*	22.8	28	
10	NACZ-1/2-0.44-28	0.44	½	1.3	5420	37.4	28	
11	NACZ-1/2-0.47-28	0.47	½	1.3	4910	33.9	28	
12	NACZ-1/2-0.50-28	0.50	½	1.3	4220	29.1	28	
13	NACZ-3/4-0.44-28	0.44	¾	1.9	5300	36.5	28	
14	NACZ-3/4-0.47-28	0.47	¾	1.9	5340	36.8	28	
15	NACZ-3/4-0.50-28	0.50	¾	1.9	5120*	35.3	28	
16	NACZ-1-0.44-28	0.44	1	2.5	5160	35.6	28	
17	NACZ-1-0.47-28	0.47	1	2.5	4570	31.5	28	
18	NACZ-1-0.50-28	0.50	1	2.5	4910	33.9	28	

- The case of maximum size of the aggregate equal to ½ inch (1.3 cm): the compressive strengths of specimens made with RPCC aggregate and WCR = 0.44 and 0.47 were 3.1% and 6.1%, respectively, larger than that of the specimens made with natural aggregate and WCR = 0.5. This results show that f'c of concrete made with RPCC aggregate gives a comparable value to that of concrete made with natural aggregate by decreasing the WCR.

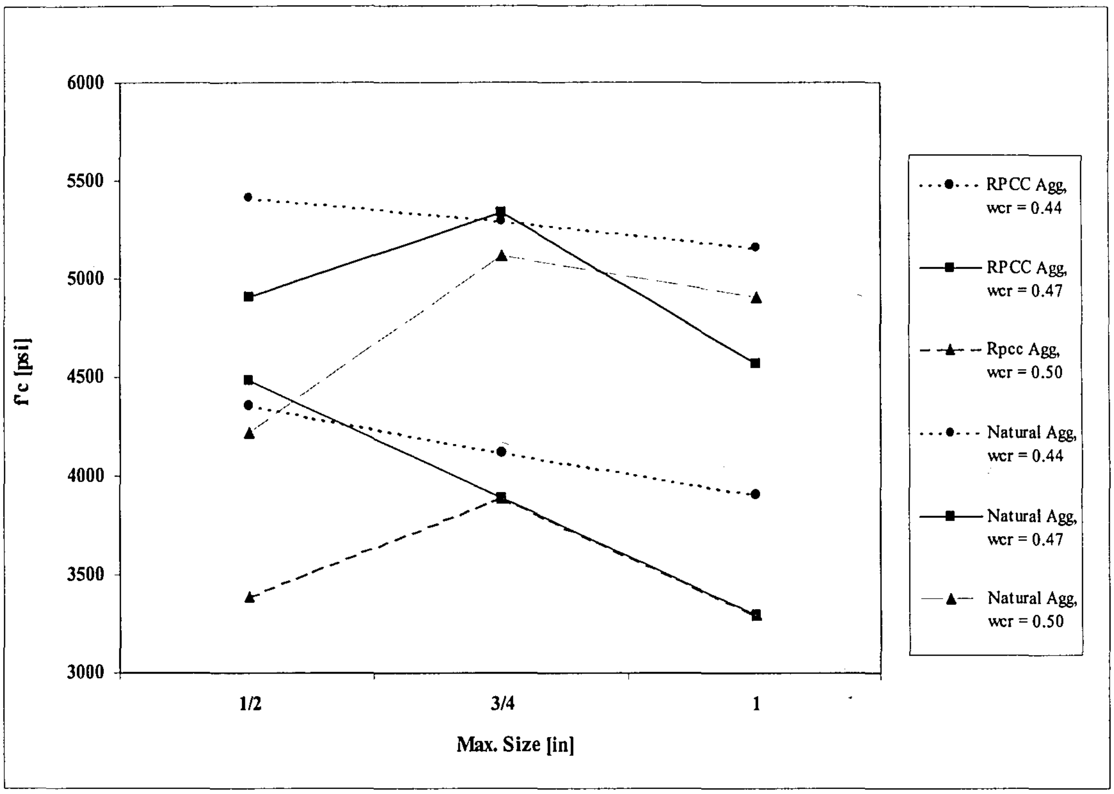

Figure 4.6. Compressive Strength Versus Maximum Size of the Aggregate.

- The case of WCR = 0.47: the f'c values of specimens made with recycled concrete with maximum size of the aggregate equal to ½ inch (1.3 cm), was 1.9% smaller than that of the specimens made with natural aggregate and maximum size of the aggregate equals to 1 inch (2.5 cm). This results show that f'c of concrete made with RPCC aggregate gives a comparable value to that of concrete made with natural aggregate by decreasing the maximum size of the aggregate of the first one.

4. 5. Shear Tests

Four shear tests were performed. The normal loads applied were 500 lb (2.224 kN), 750 lb (3.336 kN), 1000 lb (4.448 kN), and 1250 lb (5.560 kN). 92 lb (0.409 kN) were added to each vertical applied load, corresponding to the cover plate weight of the shear box. The results from these four experiments can be seen in Figure 4.7. Table 4.10 contains a summary of the Horizontal Displacement, Normal and Shear Forces, and Normal and Shear Stresses at failure. Figure 4.8 shows Shear Stress versus Shear Strain at failure (failure envelope).

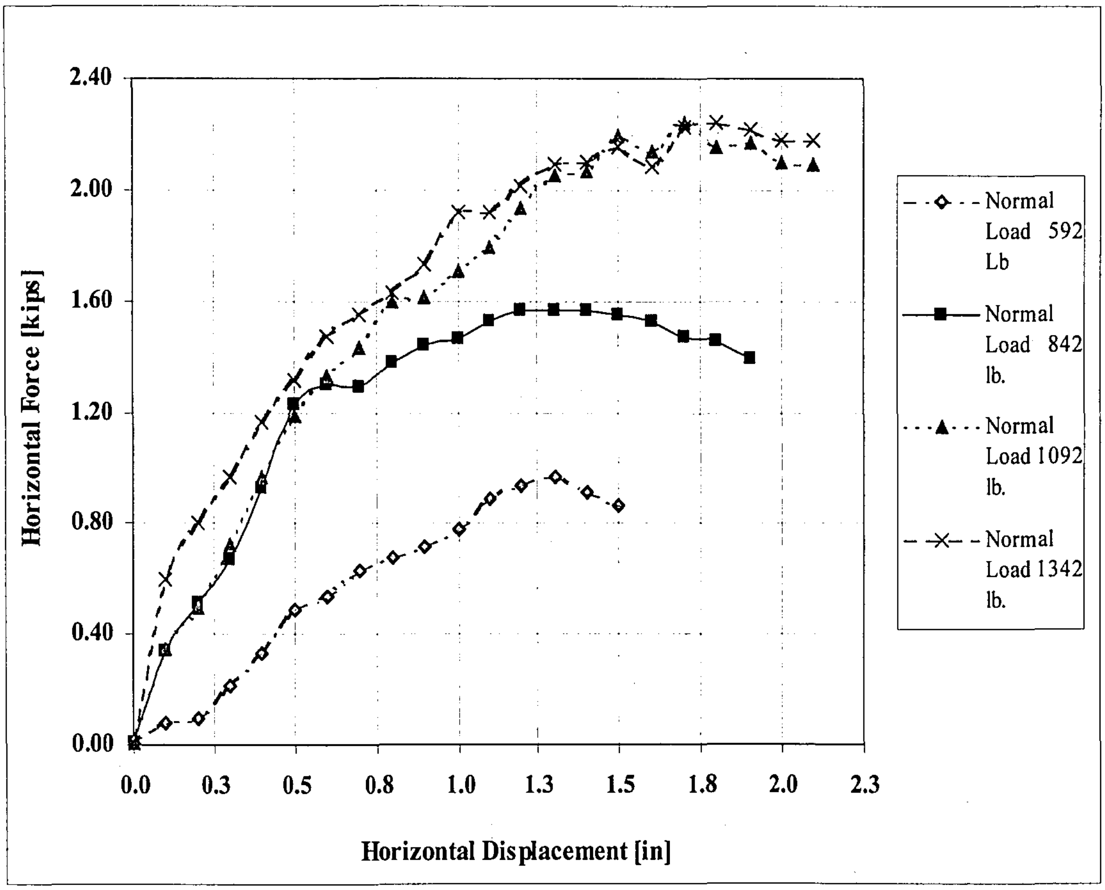

Figure 4.7. Horizontal Force Versus Horizontal Displacement.

Table 4.10. Shear Strain, Normal and Shear Stress at Failure.

No	**Horizontal Displacement**		**Shear Load**		**Shear Stress** τ_f		**Normal Force**		**Normal Stress** σ_f	
	[in]	[cm]	[lb]	[kN]	[psi]	[kPa]	[lb]	[kN]	[psi]	[kPa]
1	1.3	3.3	969	4.310	1.68	11.58	592	2.633	1.03	71.01
2	1.4	3.6	1569	6.979	2.72	18.75	842	3.745	1.46	10.07
3	1.7	4.3	2197	9.773	3.82	26.34	1092	4.857	1.90	13.10
4	1.8	4.6	2246	9.991	3.90	26.89	1342	5.970	2.33	16.06

The result from the application of the least squares method was a linear relationship $\tau-\sigma$ described as follows:

$$\tau_f = \sigma_f * \tan(\phi_f) \tag{4.13}$$

τ_f: Shearing stress at failure.

σ_f: normal stress at failure.

ϕ_f= 60.7°, friction angle at failure

The value for ϕ_f was larger than the values in Table 3.6. This may be due to the characteristic shape of the RPCC aggregate (highly angular), which could produce a greater interlocking between particles and therefore, a greater resistance to movement across the failure plane than that of a typical soil like gravel. The results obtained in this test indicated that RPCC material presented an excellent behavior under shearing solicitations. The material used in the shear tests was material retained by sieve No.4, principally coarse aggregate.

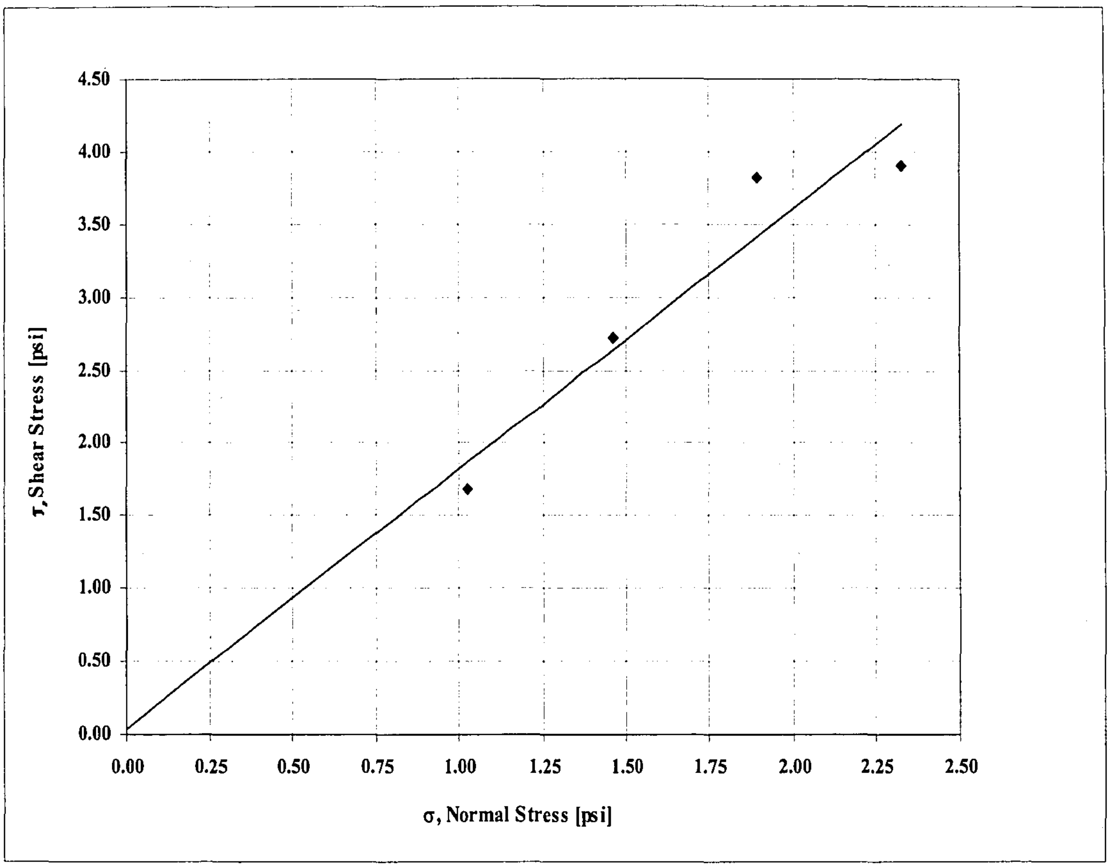

Figure 4.8. Failure Envelope for RPCC Aggregate.

CHAPTER 5. CONCLUSIONS AND RECOMMENDATIONS.

The purpose of this research was to study the behavior of RPCC aggregates in Portland cement concrete and embankment. For the first case, several batches of concrete were prepared with RPCC aggregate as well as natural aggregate. Several parameters were varied from batch to batch to understand their influence, including water cement ratio and maximum size of the aggregate. The design method and specifications used were the same for all batches prepared. Absorption and specific gravity test were performed on recycled and natural coarse aggregate, since these values play an essential role in concrete mixture design. Standard tests used to certify the quality of freshly mixed and hardened concrete with natural aggregate were performed on concrete with recycled and natural aggregate, including slump test and compression tests. For the second case, shear tests were performed on RPCC aggregate with the objective of obtaining the failure envelope and the friction angle. The conclusions and recommendations from the tests made and the results presented in Chapter 4, are presented in the following paragraphs:

1. The difference in properties such as specific gravity and absorption was important. The specific gravity of RPCC aggregate is lower than that of natural aggregate. This has immediate consequences: first, for a given volume of material, the weight needed would be less and therefore using RPCC material would be cheaper than using conventional one. Second, because specific gravity is a parameter used in mixture design, it influences

the final content of the batches of concrete. A lower specific gravity implies less fine content in the concrete compared to a concrete of similar characteristics but made from natural aggregates. The difference in fine material, in this case 14.2%, could affect the workability of the freshly mixed concrete; it may be that less fine content can result in a more workable and plastic concrete. On the other hand, the absorption resulted almost 4 times larger for RPCC aggregate. The original value of recycled material was 4.0%. If the absorption value were estimated as 3%, the error in the estimation of the absorbed water would be 25% of the original absorbed water, approximately, then the aggregate would absorb part of the mixture water reducing the water cement ratio and the slump in 1.5 inches (3.8 cm) approximately (8). Therefore, it is strongly recommended to monitor regularly the properties of the recycled material in order to get a well designed concrete. It is important to keep in mind that RPCC material is made from different sources of concrete, which affects the specific gravity and absorption values.

2. From the slump tests, for a given water cement ratio, the concrete made from RPCC aggregate shows a higher slump, level of workability and plasticity than a similar concrete made with natural aggregate. It implies a higher sensitivity to the water cement ratio from freshly mixed concrete made with RPCC aggregate, and, consequently, to the quantity of water. This suggests that concrete made from recycled aggregate needs less water content than

similar concrete made from natural aggregate, therefore helping reduce the water cement ratio, improving the compressive strength, and without affecting the workability of the concrete.

3. From the compression tests at different ages, the compressive strength as a function of the concrete age resulted in weaker hardened concrete made with RPCC aggregate than concrete with similar characteristic but with natural aggregate. The difference in compressive strength between both concretes decreased with the age. Moreover, the curves that describe these relationships suggest that as the time increases the compressive strength from concrete made with recycled aggregate tends to have a comparable value to that of concrete made natural aggregate.

4. From the compressive strength versus water cement ratio results (WCR), the compressive strength of concrete made with RPCC aggregate was always weaker than that of concrete made with natural aggregate. Here, the significant finding was that, given the models of f'c for both concretes, a relation between WCR specified for the concrete made from the natural aggregate (WCR_{Nat}) and WCR specified for the concrete made from the RPCC aggregate (WCR_{RPCC}) might be determined. Hence, once f'c and WCR are specified for a concrete made with natural aggregate, it would be possible to find WCR_{RPCC} for the same f'c. This may help modify the mixture design for concrete made with RPCC aggregate in order to get a

concrete with the same characteristics as that made from conventional materials.

5. From the results of f'c versus slump, the compressive strength of concrete made with RPCC aggregate was always weaker than that of concrete made with natural aggregate. On the other hand, the difference of compressive strength between concretes was smaller using the models of f'c as a function of the slump than as a function of WCR. In general, models of compressive strength as a function of water cement ratio tend to be more accurate.

6. From the results of f'c versus maximum size of the aggregate, with the use of smaller particle size together with a smaller water cement ratio it is possible to improve the compressive strength of the concrete. The data obtained from these test were very few and the dispersion was important, therefore the relation between f'c and maximum size of the aggregate was not modeled.

7. From the shear tests, RPCC material can develop a high friction angle at failure, which makes the use of these material in embankments highly recommended. As an alternative RPCC aggregate could be mixed with a material of lower quality, making its use more economically attractive.

Finally, it seems possible to find a way to relate the existing mixture design method for concrete using natural material to the mixture design using recycled coarse aggregate, and ensuring a good quality product, by changing some parameter like desired slump, water content, or maximum size of the aggregate. These parameters might not affect the final cost of the concrete, making the use of the recycled material economically attractive.

Further studies are needed with larger size of samples to determine more accurately the relationship between the parameters mentioned above and to implement a similar mixture design method for concrete made with RPCC to that already existent for conventional material. More studies about the influence of changing the maximum size of the aggregate should be done.

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