AMERICAN UNIVERSITY OF BEIRUT

SUSTAINABLE CONCRETE USING RECYCLED AGGREGATES

by
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AN ABSTRACT OF THE THESIS OF

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Recycled aggregate concrete (RAC) is a sustainable and renewable green concrete that is prepared by partial substitution of natural aggregates with recycled and reused aggregates. The application of RAC effectively resolves the shortage problem in natural aggregates and the concrete batch plants waste disposal of old cylinders. The proposed research is a two-phase program. The objective of the first phase is to achieve a concrete mix that fits the criteria of high performance concrete with partial substitution of natural aggregates with recycled aggregates. The trial batches will investigate the compatibility of the natural and recycled aggregates in concrete. The objective of the second phase is to assess the flexure, shear, and bond and anchorage characteristics of reinforcing bars embedded in structural concrete elements prepared using the optimum RAC batch achieved in the first phase. The significance of the proposed research program is three-fold. Attaining a RAC mix using local available recycled material will have a significant implication on the concrete industry in Lebanon, and will mitigate the construction waste disposal problem. The applications will be in normal strength reinforced concrete. The significance of the research is also reflected in the need to investigate whether the partial substitution of natural aggregates with recycled aggregates would not lead to reduction in the flexural and shear strength of reinforced concrete elements and in the bond characteristics of reinforcing bars anchored in these elements. What is of utmost importance is to use the data of the second phase of the proposed research program along with available data in the literature to verify the validity of the current design specifications set by the available codes of practice as related to RAC. The research conclusions related to appropriate RAC mixes are spreading faster than the development of appropriate design specifications.

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CHAPTER I

INTRODUCTION

A. Introduction

In the last few years, the production of construction wastes has been increasing at a large pace in Lebanon. It is due to the big boost in construction activities that led to the demolition of a big number of existing old buildings either because of the limited land for new development or due to the fact that existing buildings are structurally defected. Another reason that caused a boom in demolition waste production was the frequent wars that occurred in Lebanon during the last few decades including the 2006 Israeli war on Lebanon and the Naher El Bared conflict. Another source of construction waste comes from the concrete production procedure itself which includes sampling standard concrete cylinders in significant numbers for each cubic meter of concrete produced. The tested concrete cylinders sum up to a significant portion of the dumped construction waste material. The accumulation of such demolition waste had had detrimental impact Lebanon’s environment given the lack of plans and methods to manage, handle, and dispose dismantled waste properly.

Conventional concrete which is the most widely used construction material worldwide has been claimed not to be environmentally friendly. Negative concerns include the depletion of natural resources, high energy consumption and construction waste disposal. Therefore, recycled aggregate concrete (RAC) would propose a potential solution for the depletion of natural resources and the disposal of construction waste material, by the partial substitution of natural or crushed limestone aggregates with recycled aggregates.

According to a study by the Federal Highway Association (FHWA) in 2004, thirty eight American States recycle concrete as an aggregate base and eleven States incorporate recycled aggregates into newly produced concrete. The states that use RAC report that this concrete equally performs as concrete prepared with natural aggregates.

According to the ACI-committee-555 report (2001), recycling of concrete is a relatively simple process. It involves breaking, removing, and crushing existing concrete into a material with a specified size and quality. The quality of recycled aggregate concrete is very dependent on the quality of the recycled material used. Reinforcing steel and other embedded items, if any, must be removed, and care must be taken to prevent contamination by other materials that can be troublesome, such as asphalt, soil and clay balls, chlorides, glass, gypsum board, sealants, paper, plaster, wood, and roofing materials.

Advantages and benefits of recycled aggregate concrete include:

1. Preserving natural resources
2. Alleviation of the waste disposal problem
3. Production of a sustainable and green concrete material
4. Alleviation of environmental impacts and satisfaction of green codes requirements by the use of sustainable concrete
5. Sustainable concrete satisfies the requirement of green codes

B. Research Objectives

The sustainable and green advantages of recycled aggregate concrete prompted the initiation of a multi-phase research program at the American University of Beirut. The objective of the first phase is to perform different trial concrete batches at the Concrete Materials Laboratory to achieve an optimum mix that fits the criteria of RAC as far as workability and strength requirements. The trial batches shall investigate the compatibility of the natural and recycled coarse aggregate material in order to find an optimum mix. Mix proportioning techniques such as the ACI 555 committee procedure or the EMV (equivalent mortar volume) method shall be compared and tested. Any need for modifying the proportioning techniques as per the characteristics of local recycled aggregate resources will also be examined. Both normal strength and high strength concrete mixes will be tested.

The objective of the second phase is to assess the flexure, shear, and bond & anchorage characteristics of reinforcing bars embedded in structural elements cast using the optimum RAC batch achieved in the first phase. It is very significant to conduct a research program to determine the influence of the main factors on strength and to get a better insight in the difference in strength and behavior between conventional concrete and recycled aggregate concrete. The research data of the second phase along with the available data in the literature will be used to check the validity of the ACI 318 predictions and estimations of shear and flexural performance in terms of shear capacities, flexural capacities, cracking moments and modes of failure of structural members made with RAC mixes.

C. Research Significance

The significance of the proposed research program is three-fold. Attaining a RAC mix using local available recycled and natural materials will have a significant implication on the concrete industry in Lebanon since the industry does not have the know-how. The applications will be in normal strength reinforced concrete. The significance of the research is also reflected in the need to investigate the hypothesis that the partial substitution of natural aggregates with recycled aggregates would lead to reduction in the flexural and shear strength of reinforced concrete elements and in the bond characteristics of reinforcing bars anchored in RAC elements compared with the conventional concrete elements. The ACI structural journal has no published papers that discuss the shear strength and shear performance of reinforced RAC members; only one ACI paper published discussing the flexural strength of reinforced RAC beams. This shows a lack of research in that domain. The outcomes of the second phase and the available data in the literature will be used to check the validity of the ACI 318 predictions and estimations for flexural and shear performance and capacities when applied to reinforced RAC structural members. This will target the study of the criteria related to the questioning of the need to develop new design recommendations specific to RAC members and thus grow confidence in the use of RAC structural members in construction industry.

D. Research Methodology

Phase 1

Since the Lebanese concrete industry does not have the experience or the know-how to produce recycled aggregate concrete, an extensive concrete batching and testing program will be conducted to achieve an optimum concrete mix which fits the criteria of RAC as far as workability, homogeneity and performance. The trial batches will check the compatibility of the natural and recycled fine and coarse aggregate materials in the concrete industry. Tests on the different trial RAC batches will include slump test to assure that the concrete mixture qualifies as RAC. Other tests include 6x12 in. standard cylinders to check the compressive strength, tensile splitting strength, and modulus of elasticity. Standard beam tests will be used to check the flexural strength.

Phase 2

The second phase will be designed to assess the flexure, shear, and bond and anchorage characteristics of reinforcing bars embedded in RAC reinforced concrete structural elements. The optimum RAC concrete mix achieved in Phase 1 will be used to prepare the reinforced concrete specimens. Eighteen full-scale normal strength concrete simply supported beam specimens will be tested. Each flexural beam will be reinforced with two main bars and adequate stirrups or shear reinforcement to avoid shear failure. Each shear beam will be reinforced with two main bars but with no stirrups. Each bond beam will be reinforced with bars spliced in a constant moment region at mid-span. The splice length will be chosen in such a way that the beams would fail in bond splitting of the concrete cover in the splice region.

The main variables in phase 1 and 2 are the concrete type (RAC or conventional concrete), the mode of failure (shear or flexural), and the percentage substitution of natural aggregates with recycled aggregates. For each set of variables, two companion beams identical except for the concrete type will be tested. At each load increment, deflection at mid-span will be recorded and flexural cracks will be marked. The effect of RAC will be evaluated by comparing the performance of the companion specimens. Comparison is based on the mode of failure, ultimate load, and general load-deflection behavior.

CHAPTER II

BACKGROUND & LITERATURE REVIEW

A. Research related to the Mechanical properties of RAC

Recycled aggregate concrete has been of interest for many researchers worldwide. The performance of recycled aggregate concrete can vary based on the recycled aggregate demolishing source and with the substituted aggregate quality and quantity. Extensive international research is available due to the interest of recycled concrete in terms of the environmental impact concerns and sustainable development.

The ACI-committee-555 (2001) considers the demolition techniques, the recycled aggregates preparation methods, and the recycled aggregate concrete mixes. The selection of the water-cement ratio is the most critical part of controlling the concrete strength. There is an excellent correlation between water-cement ratio and the compressive and flexural strengths. The water-cement ratio is valid for recycled aggregate concrete as it is for conventional concrete made with natural materials, but only the level of strength development would be reduced. To produce similar consistency and workability, 5% additional water was found to be required for a recycled coarse aggregate concrete. In other cases approximately 15% additional water was needed to produce the same workability for both fine and coarse recycled aggregate concrete. The bleeding from recycled aggregate concrete was found to be slightly less than that of conventional concrete using natural aggregates. Recycled fine aggregates, as they come from the crusher, are somewhat coarser and more angular than needed to produce good quality concrete. Also, studies indicated that this coarseness and increased angularity are the reasons that concrete made with these materials tends to be somewhat harsh and of less workability. Thus, adding a portion of finer natural blending sand to the recycled sand can produce materials with suitable fresh concrete properties. Recycled aggregates generally have densities slightly less than the original materials used. Generally, variations in water-cement ratios of the concrete do not appear to have a significant impact on density. One main difference between recycled aggregates and natural aggregates is the higher water absorption, probably due to the absorption of the old cement mortar attached to the recycled aggregate particles. As for the Los Angeles Abrasion loss test, the recycled concrete aggregates produced from all but the poorest quality recycled concrete can be expected to pass ASTM requirements. The variety of contaminants that could be found in recycled aggregates as a result of demolition of existing structures can severely degrade the strengths of the RAC. Some of these materials are plaster, soil, wood, gypsum, asphalt, plastic, or rubber. Allowable amounts of deleterious impurities in recycled aggregates are provided. The compressive strength of recycled concrete depends on the strength of the original concrete and it is largely controlled by a combination of the water-cement ratio (w/c) of the original concrete and the w/c of the recycled concrete. The majority of researchers found that the compressive strength for concrete manufactured from recycled coarse and fine aggregates was lower than that of concrete made with all naturally occurring materials by 15 to 40%.

Evangelista et al. (2007) used fine recycled concrete aggregates to partially or globally replace natural fine aggregates (sand) in the production of structural concrete. An experimental campaign was implemented in order to monitor the mechanical behaviour of such concrete. The results of the compressive strength, split tensile strength, modulus of elasticity and abrasion resistance, were reported. It was found reasonable to assume that the use of fine recycled concrete aggregates does not jeopardize the mechanical properties of concrete, for replacement ratios up to 30%.

In a study by Rahal (2007), the results of an experimental study on some of the mechanical properties of recycled aggregate concrete as compared to those of the conventional normal aggregate concrete were reported. The study investigated the development of cube compressive strength and the indirect shear strength at ages of 1, 3, 7, 14, 28 and 56 days; the strains at maximum compressive stress; and the modulus of elasticity tested by using standard 15 x 30 cm (6 x 12 in) concrete cylinders at 28 days. The results show that the 28-day cube and cylinder compressive strength, and the indirect shear strength of recycled aggregate concrete were on the average 90% of those of natural aggregate concrete with the same mix proportions. For concrete with cylinder compressive strengths between 25 and 30 MPa, the modulus of elasticity of RAC was only 3% lower than that of natural aggregate concrete (NAC). The trends in the development of compressive and shear strength and the strain at peak stress in recycled aggregate concrete were similar to those in natural aggregate concrete.

Etxeberria et al. (2007) used the recycled coarse aggregates obtained from crushed concrete for concrete production. Four different recycled aggregate concretes were produced made with 0%, 25%, 50% and 100% replacement of natural aggregates by recycled coarse aggregates, respectively. Recycled aggregates were used at wet condition, but not saturated, to control their fresh concrete properties, effective w/c ratio and lower strength variability. The influence of the order of materials used in concrete production (made with recycled aggregates) with respect to improvement in the splitting tensile strength was analyzed. The lower modulus of elasticity of recycled coarse aggregate concretes with respect to conventional concretes was measured verifying the numeral models proposed by several researchers.

In a study by Rao et al. (2007), a summary of the effect of use of recycled aggregate on the properties of fresh and hardened concrete was discussed. The paper concludes by identifying some of the major barriers in more widespread use of recycled aggregate concrete (RAC), including lack of awareness, lack of government support, non-existence of specifications/codes for reusing these aggregates in new concrete.

Gokce et al. (2004) investigated the freezing and thawing resistance of RAC. Air-entrained and non-air-entrained concretes with a water/cement ratio of 0.45 were recycled at the crushing age of 1 year to obtain the coarse aggregates used in the investigation. The recycling process was performed in three stages to produce recycled coarse aggregates with different adhered mortar contents. The results showed that recycled coarse aggregate produced from non-air-entrained concrete caused poor freezing and thawing resistance in concrete even when the newly produced RAC had proper air entrainment. Microstructural studies indicated that non-air-entrained adhered mortar caused disintegration of the recycled coarse aggregate in itself and disrupted the surrounding new mortar after a limited number of freezing and thawing cycles.

Minimizing non-air-entrained adhered mortar or enhancing the performance of new surrounding matrix could not give satisfactory results for a long freezing and thawing exposure.

S. F. U. Ahmed (2012) published a paper in the Journal of Material in Civil Engineering reporting the properties of concrete containing recycled coarse aggregate (RCA) source from local construction and demolition (C&D) wastes and fly ash (FA) sourced from Western Australia (WA). The RCAwas used as 25, 50, 75 and 100% (by wt.) replacement of natural coarse aggregate (NCA). In addition, the effect of 40% (by wt.) class F fly ash as partial replacement of cement on the properties of recycled aggregate concrete is also evaluated. The properties of concrete evaluated are the compressive strength, indirect tensile strength, flexural strength and water absorption. All properties are measured at 7, 28, 56 and 91 days. The results show that, better compressive, tensile and flexural strength of concrete containing 25% RCA as partial replacement of NCA could be obtained in recycled aggregate concrete. However, in the case of recycled aggregate concretes containing 40% fly ash the compressive strength at later ages such as at 56 and 91 days was increased but the indirect tensile and flexural strengths decreased at all ages. It is observed that the water absorption is decreased as RCA content increased. It was also observed that the water absorption is decreased significantly in recycled aggregate concretes containing 40% fly ash at all ages.

When summing up the amount of research in this field, the ACI material journal, concrete international publications, journal proceedings and ACI special/symposium publications archives have 58 published papers that discuss a range of topics related to the physical and mechanical properties of concrete produced by recycled aggregates. These papers were published between the years 1977 and 2012. A list of the topics is presented below:

1. ACI Material Journal (10 papers)

- Role of Chemical and Mineral Admixtures on the Physical Properties and Frost-Resistance of Recycled Aggregate Concrete (1998).
- Crack Propagation in Recycled Aggregate Concrete under Uniaxial Compressive Loading (2012).
- Performance of Portland/Silica Fume Cement Concrete Produced with Recycled Concrete Aggregate (2012).
- Performance and Properties of Structural Concrete Made with Recycled Concrete Aggregate (2003).
- Resistance to Freezing and Thawing of Recycled Aggregate Concrete (2003).
- Use of Recycled Rubber Tires in Normal and High-Strength Concretes (2009).
- Influence of Type and Replacement Level of Recycled Aggregates on Concrete Properties (2008).
- Strengths of Recycled Aggregate Concrete Made Using Field-Demolished Concrete as Aggregate (1996).
- Concrete made with coarse concrete aggregate: Influence of Curing on Durability (2012).

2. ACI Concrete International (10 papers)

- Strength of Recycled Concrete Made From Crushed Concrete Coarse Aggregate (1983).
- Use of Recycled Aggregate in Plain Fiber-Reinforced Shotcrete (2000).
- Demolition and Reuse of Concrete and Masonry (1989).
- Soil-Cement from Recycled Pavement Bases and Surfaces (1989).
- Proportioning Concrete Mixtures with Recycled Concrete Aggregate (2010).
- Reincarnation of Concrete, February (2005).
- The Properties of Recycled Concrete (1997).
- Recycled Concrete As Aggregate (1986).
- Drying Shrinkage Behavior Of Recycled Aggregate Concrete (1996).
- Greener Concrete Using Recycled Materials (2002).

3. Journal proceedings (4 papers)

- Waste concrete as Aggregate for new concrete (1977).
- Elasticity and drying shrinkage of RAC (1985).
- Recycled concrete as a source of aggregate (1977).
- Properties of RAC as affected by admixtures in original concrete (1984).

4. ACI special/symposium publications (34 papers)

- Effectiveness of Super-plasticizers Incorporating Shrinkage-Reducing Admixture in Recycled-Aggregate Concrete (2006).
- Shrinkage of Concrete with Replacement of Aggregate with Recycled Concrete Aggregate (2002).
- Creep of Concrete with Substitution of Normal Aggregate by Recycled Concrete Aggregate (2002).
- Recent Trends in Recycling of Concrete Waste and Use of Recycled Aggregate Concrete in Japan (2004).
- Repercussions on Concrete Permeability Due to Recycled Concrete Aggregate (2001).
- Use of Recycled Concrete Powder in Self-Compacting Concrete (2001).
- Properties of Concrete with Recycled Concrete Coarse Aggregates (2005).
- Use of Recycled Concrete as Aggregates for the Construction of Fish Reefs (2001).
- The Role of Recycled Aggregates in Self-Compacting Concrete (2004).
- Guidance for Recycled Concrete Aggregate Use in the Highway Environment (2004).
- Mitigating Alkali Silica Reaction in Recycled Concrete (2004).
- Sustainable and Durable Reinforced Concrete Construction (2002).
- Performance of High-Grade Concrete with Full Substitution of Aggregates by Recycled Concrete (2001).
- The Risk of Corrosion of Steel in Recycled Aggregate Concrete (2003).

- Innovative Methods for Water Content Control of Recycled Aggregate Concrete (2001).
- High Quality Recycled Aggregate Concrete (HiRAC) Processed by Decompression and Rapid Release (2001).
- Admixtures on Performance and Economics of Recycled Aggregate Concrete (2001).
- Feasibility and feasability and Performance of Recycled Aggregate in Concrete Containing Fly Ash for Sustainable Buildings (2001).
- Strength and Durability Parameters of an Environmentally Friendly Concrete (2012).
- Self-Compacting Concrete: What Is New? (2003).
- Aggregates from Residual Concrete (2012).
- Durability of Concrete with Recycled Fine Aggregate (2006).
- Mechanical Properties, Drying Shrinkage and Resistance to Freezing and Thawing of Concrete Using Recycled Aggregate (1998).
- Use of Recycled Concrete Aggregates in Hot-Mix Asphalt (2006).
- Recycling of Demolished Concrete (2001).
- New Method Manufacturing High-Quality Recycled Aggregates by Mechanical Grinding (2006).
- Influence of Storage Conditions and Concrete Composition on the Effectiveness of Different Silica Fumes Against ASR (1998).
- Reliability-Based Life Cycle Assessment of Green Concrete Structures (2012).
- Application of Recycled Concrete for Structural Concrete- Experimental Study on the Quality of Recycled Aggregate and Recycled Aggregate Concrete (1998).
- Improvement of Concrete with Recycled Aggregate (2000).
- SP-219: Recycling Concrete and other Materials for Sustainable Development (2004).

- The Stabilization of Aqueous Heavy Metal Species Using Recycled Concrete Fines (2001).
- Effects of Recycled Aggregate Characteristics on Performance Parameters of Recycled Aggregate Concrete (2000).

B. Research related to the structural performance of RAC members.

The large reported research investigating the properties of RAC in terms of compressive strength, split tensile strength, modulus of elasticity, indirect shear strength, resistance to freeze and thaw, and workability, surpassed the amount of research in the field of testing the current design recommendations validity with RCA structural members, and in the field of developing new design bases if needed. Only three papers discussing the shear capacity and flexural capacity of RAC were published up-to-date in ACI journals or publications, one of which was published in an ACI Special/Symposium publication and the other two in the ACI Structural Journal.

1. ACI Special/Symposium publication (1 paper)

Han et al. (2001) performed limited experimental research on the shear capacity of reinforced RAC beams. The variables in the test program were the span/depth ratio (1.5, 2, 3, and 4), the aggregate type (natural, washed recycled, and non-washed recycled), and percent of shear reinforcement (0, 0.089, 0.507, and 0.823). The research readings were for crack patterns, failure modes, load-deflection behavior, and predicted versus measured capacities. The research was limited to 12 simply supported beams, and concluded that all beams with web reinforcement failed in flexure. It was reported that ACI 318 Equations 11-3 and 11-5 overestimated the shear capacity of RAC beams with span/depth ration greater than 3. The paper stressed that further investigation should be made to test the conclusions.

2. ACI StructuralJ (2 papers)

Gholamreza el al. (2009) studied the flexural performance of reinforced RCA beams. The work of this research program was published in the ACI Structural Journal. The variables tested were the type of aggregate replaced (only coarse aggregate substitution), method of concrete mix proportioning (limited to the EMV method), and the percentages of flexural reinforcement in beams (minimum, average, maximum and double reinforced sections). The research measured values of cracked moments, yield, and ultimate moments in addition to service, yield, and ultimate deflections. The ratio of observed service deflection to predicted service deflection ratio was evaluated according to predictions following the ACI 318, EC2, and the moment curvature relationships. The research concluded that RCA beams compared well with conventional concrete at service and ultimate loads in terms of flexural performance and the general flexural theory-given that the EMV proportioning method is used- is valid. Yet the predicted cracking moments of tested beams based on the ACI 318 relation to the modulus of rupture were over-estimated and further investigation was required to test these predictions.

A 1/4-scale model of a two-bay, two-span, six-story recycled aggregate concrete (RAC) frame structure was tested on a shake table (2012). Dynamic characteristics of the structure were assessed through white-noise tests. The building suffered increasing levels of damage as excitations became more severe. The damage ranged from cracking to crushing of concrete. Nevertheless, the building did not collapse under base excitations with peak ground acceleration (PGA) up to 1.170g. The inter-story drift, seismic force, inter-story shear, hysteresis curves, capacity curve, ductility coefficient, and stiffness degradation were computed and analyzed. Furthermore, general behavior of the RAC frame structure model was compared and discussed with that of the normal aggregate concrete (NAC) frame structure. The test results demonstrate that it was feasible to apply and popularize RAC frame structures less than six stories high in seismic regions and the Sichuan Wenchuan post-earthquake reconstruction area.

3. Other papers:

Sun-Woo Kim et al. (2012) discussed the Influence of recycled coarse aggregates on the bond behavior of deformed bars in concrete. To investigate the bond behavior of deformed bars in recycled aggregate concrete (RAC), 144 tests were performed. The following variables included: the aggregate size, four types of recycled coarse aggregate (RAC) replacement ratios, two reinforcing bar directions (vertical and horizontal), and two reinforcing bar locations (75 and 225 mm from the bottom). In addition, the effect of concrete aging on the bond behavior between the bar and the concrete was evaluated. Based on the test results, the RAC-I specimens (with 20 mm of maximum RCA size) had a greater bond strength than the RAC-II specimens (with 25 mm of maximum RCA size) under the same RCA replacement ratio. Thus, the bond strength of RAC is affected by the aggregate size because the shape of the RAC is generally spherical. For both RAC-I and -II specimens, as RCA replacement ratio increased, compressive strength showed a tendency to decrease proportionally. In terms of aging, regardless of the RAC replacement ratio, RAC-I pullout specimens showed similar bond strength under the same age although the compressive strength showed a downward trend with the RAC replacement ratio. In view of the top-bar effect, a significant difference was detected between the top and bottom bars at all ages. In particular, the bond stress was not uniformly distributed along the length of the bar in the RAC-II specimens due to settlement of the coarse aggregates.

It should be noted that the amount of work and research in the fields regarding the physical properties of RAC and the proportioning techniques exceeds greatly the minimal amount of research and published papers in the fields regarding the structural performance of members made from RAC and the validity of the current specifications given in the available codes of practice when applying to RAC structural members.

CHAPTER III

ENVIRONMENTAL SIGNIFICANCE

A. Sustainable or Green Concrete

The urge of converting the building construction process into a sustainable construction process is increasing drastically with the current increase in population and therefore the high demand on building facilities. The word “sustainable” is becoming very common worldwide yet what are the key factors that help introducing this important characteristic into the construction industry. Sustainable building systems can have a direct implication on the betterment of livelihood conditions of communities.

Concrete, the most widely used construction material is claimed as a sustainable material. Unfortunately, the extraction of natural aggregates has lead to establishing human-made quarries that have drastic environmental impact on the nature and surroundings. Depletion of natural resources will definitely lead to a scarcity of conventional building material allowing to an increase in the cost of these material as the demand on such material is continuing to increase rapidly. These issues put our claim regarding the sustainability of concrete questioned.

Sustainable materials are currently widely considered and investigated in construction engineering research. Some examples of sustainable research worldwide are the use of coal fly ash, ground clay brick, and pervious paver block. Further, substantial research work has been conducted on fiber-reinforced concrete which is a concrete primarily made of a mix of hydraulic cement, aggregates, water, and reinforcing fibers.

In the present research, a study of the adequacy of replacing natural coarse aggregates with recycled coarse aggregates will be performed. The source of recycled coarse aggregates will be the tested concrete standard cylinders. These sample test cylinders are part of the concrete production process in all batch plants and after testing they are considered as a significant waste material that has no nature friendly process for its disposal.

Recycling of concrete production waste material will directly influence the sustainability of concrete on two levels. Reusing the concrete cylinders as a partial or full replacement of natural coarse aggregates will simultaneously reduce the amounts of natural coarse aggregates being used and thus help slow down the depletion process of natural resources. Recycling the cylinders into coarse aggregates that are incorporated in the concrete mix will solve the increasing waste disposal crisis.

B. Local Waste Conditions

A study that included all local batching plants was made to track the different ways those batching plants dealt with the amounts of tested standard cylinders. The majority of the responses were that the cylinders were disposed. The procedure was typically renting a pickup driver that has knowledge with disposal works and paying him to transport those cylinders and dump them at the assigned locations. Some of the batch plants mentioned giving them to the military forces that used them as part of decorative works. A list of the batching plants with their procedure of dealing with the tested cylinders is presented in Table 3.1.

Another observation was made to track the locations were the cylinders are disposed. A local driver expert in disposal works was asked to track trucks with construction waste products and the results were that all small trucks carrying a range of 3 to 5 tons of waste products are not limited to cylinders yet are compromised from a wide range of construction waste products in a central dump land in the Ouzaii district. Then larger trucks that carry up to 30 tons of waste transport those waste products to rural districts and valleys in coordination with the cities municipality. Globally all these waste products dumped in Aramoon, Bchamoon or the south area are randomly dsposed in valleys without applying any procedure to separate or reuse them. Below are figure of the piles of construction waste products.

CHAPTER IV

PHASE I: EFFECT OF RECYCLED COARSE CONCRETE AGGREGATES ON FRESH AND HARDENED CONCRETE PROPERTIES

A. Introduction

The objective of the first phase of the experimental work con was to identify and assess the effect of introducing recycled coarse concrete aggregates (RCA) into the concrete mix on the fresh and gardened concrete properties. A sequence of trial concrete mixes with varying replacement of natural coarse aggregate by recycled aggregates was carried out. The same source of the recycled concrete aggregates was maintained. A total of six different concrete mixes were prepared. The mixes were identical except for the percentage replacement (Rpl.) of natural coarse aggregates with RCA. Rpl. values of 0, 20, 40, 60, 80 and 100 percent were used. The nominal concrete compressive strength of all mixes was 28 mpa.

*RCA Recycled concrete aggregate

*Rpl. Percentage replacement of natural coarse aggregates with RCA

B. Tests of Phase 1

Tests on the different trial RAC batches will include slump for workability requirements check. Other tests include 150 x 300 mm (6x12 in.) standard cylinders to evaluate the compressive strength, the tensile splitting strength, and the modulus of elasticity. Standard beam tests were cast to evaluate the flexural strength.

- Compressive Strength Test – ASTM C39

Standard cylinders (150 x 300 mm) were prepared and tested according to ASTM C39 to determine the compressive strength at 3, 7, and 28 days. Two cylinders were tested at each test age and the average was determined and reported; i.e. 36 cylinders were tested in total.

- Flexure Beam Test – ASTM C78

Standard beam specimens (150 x 150 x 530 mm) were prepared and tested according to ASTM C78 in order to determine the flexural strength and load deflection curves. The beam specimens were tested using the MTS machine, where the load P (kN) was applied simultaneously at 2 locations, 15 cm apart, and symmetric with respect to the beam mid-span.

- Splitting Tensile Strength Test – ASTM C496

Standard cylinders (150 x 300 mm) were prepared and tested at 28 days according to ASTM C496 to determine the splitting tensile strength. The average of three tests was reported.

- Modulus of Elasticity Test – ASTM C469

The modulus of elasticity was measured, according to ASTM C469, for all mixes. Standard (150 x 300 mm) cylinder specimens were used. Each reported value is the average of three tests.

C. Constituent Materials

1. *Fine Aggregates*

Natural sand with particle sizes ranging from 1.18 mm to 0.075 mm was used in all trial mixes. Tables 3.2 and 3.3 show the sieve analysis results and the specifications of the natural sand used.

Table 4.1: Sieve Analysis - Natural Sand

Sieve #	Opening Size (mm)	%Passing
9.5	9.5	100.0
4	4.75	98.58
8	2.36	97.81
16	1.18	96.95
30	0.6	92.51
50	0.3	29.01
100	0.1	2.97
200	0.075	0

Table 4.2: Fine Aggregate Specifications

Specific Gravity (SG)	**2.62**
Absorption (%)	**0.65 %**
Fineness Modulus	**2.8**

2. Coarse Aggregates

Throughout the experimental program, two types of coarse aggregates were used, natural lime stone coarse aggregates (NCA) and recycled coarse aggregates (RCA) from tested concrete cylinders.

a. Natural Coarse Aggregates

i. Gradation Curves

All natural coarse aggregates used in this research phase were from the same source. The aggregates were sorted in two types of sizes referred to as 1 inch and ½ inch coarse aggregates. The two sizes were mixed in adequate proportions to satisfy the gradation limitation set by the ASTM standard. The chosen proportions were 40% 1_inch 60 % ½_inch natural coarse aggregates.

The gradation curves of the 1_inch natural coarse aggregate labeled NCA1 is shown in Figure 3.1 (a). It falls out of the recommended range of gradation set by the ASTM standard.

On the other hand, the gradation curve of the ½_inch natural coarse aggregate labeled NCA0.5 is shown in Figure 3.1 (b). Again this curve falls out of the recommended range set by the ASTM standard.

However when a mixture of the two sizes of the natural coarse aggregates is prepared with 40% 1_inch and 60% ½_inch sizes, then the gradation curve shown in Figure 3.1 (c) and labeled NCA, fits within the specified ASTM range.

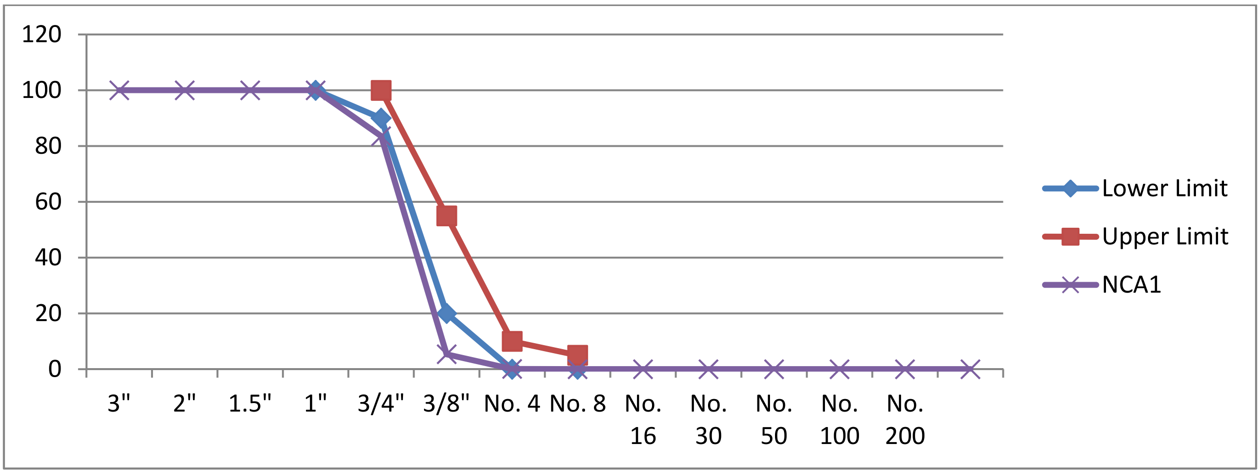

Figure 7-1 (a)

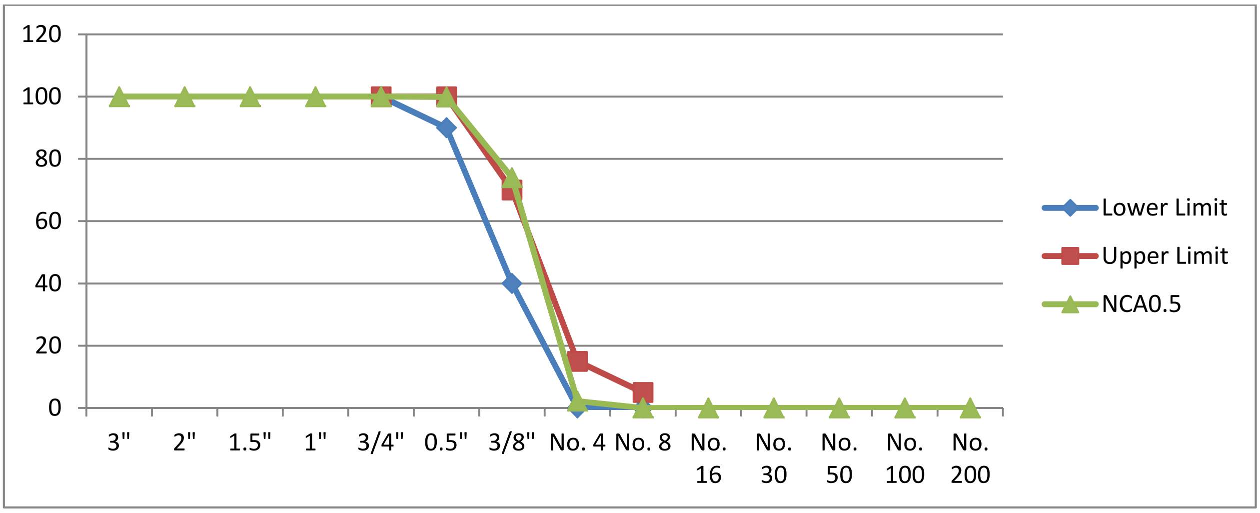

Figure 7-1 (b)

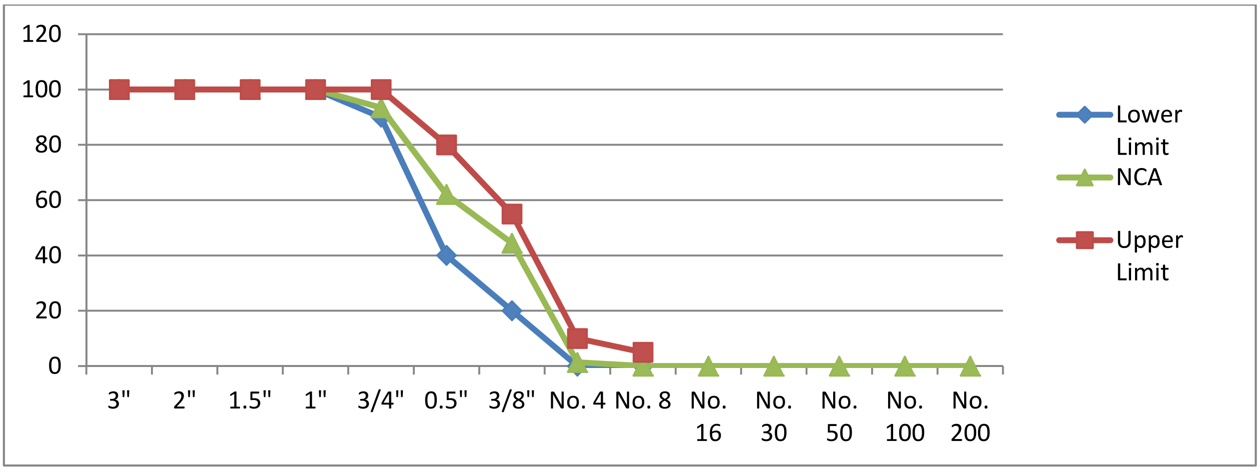

Figure 7-1 (c)

ii. Mechanical Properties

Tests to determine the dry density, absorption capacity and specific gravity of the 1-inch and ½-inch natural coarse aggregates were conducted regularly on representative samples as per the ASTM 127 standard test. Test results were consistent throughout the research. Table 3.3 below shows the values used in the mix design.

Table 4.3: Natural Coarse Aggregate Specifications

	1 in (25.4 mm)	**0.5 in (12.7 mm)**
Dry rodded Unit weight	1620 kg/m^3	1550 kg/m^3
Oven Dry Specific gravity	2.63	2.65
Absorption	1.4 %	0.8 %

b. ***Recycled Coarse Aggregates***

i. Gradation Curves

All recycled coarse aggregates used in this research were from the same source. Normal strength concrete cylinders were collected and stored at a local ready mix plant. The cylinders were the waste product of regular tests conducted at the batching plant on NSC mixes prepared and delivered to the different clients. After collection, the cylinders would be crushed and sorted into two ranges of sizes referred to as 1-inch ½-inch recycled coarse aggregates (RCA). The two sizes were mixed in adequate proportions in order to satisfy the gradation limitation set by the ASTM standard. The proportion that was chosen is 60% 1-inch and 40 % ½-inch natural coarse aggregates.

The gradation curves of the 1_inch the recycled coarse aggregate labeled RCA1 is shown in Figure 3.2 (a). It falls out of the recommended range of gradation set by the ASTM standard.

On the other hand, the gradation curve of the ½_inch natural coarse aggregate labeled RCA0.5 is shown in Figure 3.2 (b). Again this curve falls out of the recommended range set by the ASTM standard.

However when a mixture of the two sizes of the natural coarse aggregates is prepared with 60% 1_inch and 40% ½_inch sizes, then the gradation curve shown in Figure 3.2 (c) and labeled RCA, fits within the specified ASTM range.

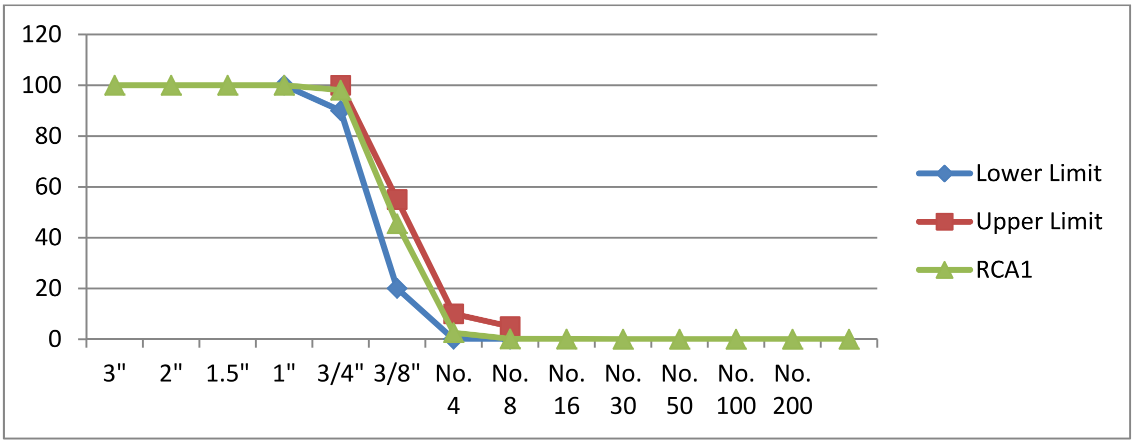

Figure 7-2 (a)

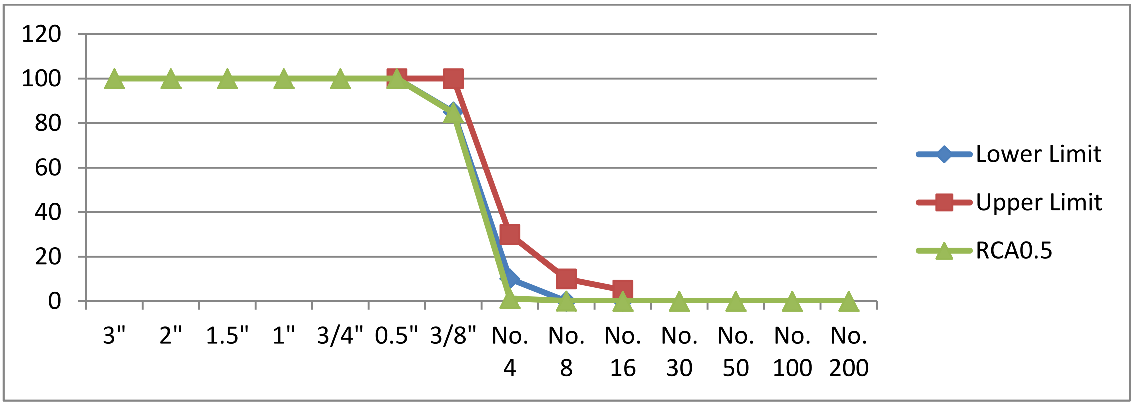

Figure 7-2 (b)

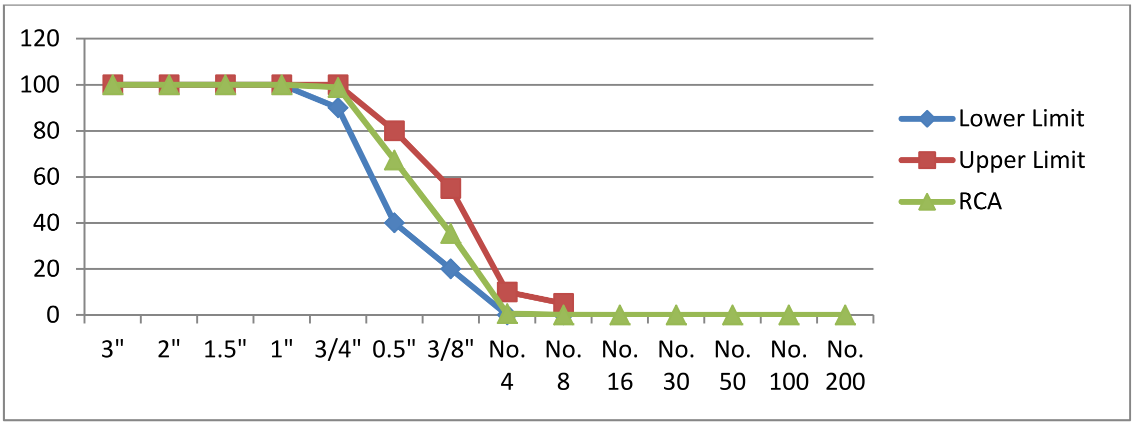

Figure 7-2 (c)

ii. Mechanical Properties

Tests to determine the dry density, absorption and specific gravity of the recycled coarse aggregates were conducted regularly on representative samples of the 1-inch and ½-inch recycled coarse aggregates as per the ASTM 127 standard test. The test results were consistent throughout the research. Table 3.4 below shows the values used in the mixed design.

Table 4.4: Recycled Coarse Aggregate Specifications

	1 in (25 mm)	0.5 in (12.7 mm)
Dry rodded Unit weight	1389 kg/m^3	1376 kg/m^3
Oven Dry Specific gravity	2.29	2.35
Absorption	5.1 %	4.8 %

According to the results of the tests to determine the physical properties of the recycled coarse aggregates, the following notes could be listed:

1) Relatively higher absorption value than NCA which is consistent with findings of previous research work. This high value of absorption is linked with the presence of the adhered mortar on the RCA surface that is expected to absorb more water.
2) A density lower by around 10% from that of NCA is also correlated to the presence of the mortar material. This is also reflected in the lower values of the specific gravity.

These differences were taken into consideration in the mix design of the different concrete mixes.

D. Mix Design Method

The ASTM tables that provide guidelines for the mix design of normal strength concrete mixtures were used to program an excel sheet capable of calculating batching weights per one cubic meter of concrete.

The following criteria and assumptions were adopted while designing any mix:

1) Concrete compressive strength of 28 MPa.
2) Slump value = 100 mm.
3) Water/Cement ratio prior to water correction due to absorption = 0.57.
4) All aggregates, fine and coarse, are used in oven dry conditions.
5) All coarse aggregates are washed from dust material prior to oven drying.
6) The water content was corrected so that the additional amount of water that will be absorbed by the RCA due to the higher absorption value was taken into consideration.

Six different mixes were designed following the same guidelines. The only variable that was altered between mixes was the percentage of replacement of natural coarse aggregate with recycled coarse aggregates. All other parameters were kept the same to insure a proper evaluation of the effect of the recycled coarse aggregates on the fresh and hardened concrete properties.

E. Description of Performed Tests

1. Fresh Concrete Tests

Abrams Slump Cone Test

Abrams cone was used to test the slump of the fresh concrete with reference to ASTM C143 standard.

2. Hardened Concrete Tests

The following hardened concrete tests were performed on normal strength concrete. Six mixes were prepared at the lab, identical except for the Rpl of NCA by RCA (0, 20, 40, 60, 80, and 100%).

a. Cylinder Compression Test

Six standard 150x300 mm cylinders were cast from each of the concrete mixes, two to be tested at 3, 7, and 28 days ages in accordance with ASTM C39. All 36 cylinders were cured in the laboratory for 28 days.

b. Splitting Tensile Test

The splitting tensile test was conducted with reference to ASTM C496. Two cylinders of each mix type were tested at the age of 28 days; a total of 12 cylinders.

c. Modulus of elasticity

The modulus of elasticity was determined based on ASTM C469, where 2 cylinders were tested for each mix type at the age of 28 days.

d. Flexure Test

The flexural strength of 150 x 150 x 530 mm plain concrete beams was determined using the third point loading method specified in ASTM C78[22]. Using the MTS machine at the lab, the beam specimen with a span length equivalent to three times its depth was subjected to concentrated loads at one-third and two-third of its span until failure. This test was performed at 28 days age on two replicate specimens for each mix type.

F. Experimental Results

Results of the standard tests conducted on the fresh and hardened properties of the different concrete batches performed in Phase I are presented in the following two sections.

1. *Fresh Properties*

All six mixes were designed and batched to meet the consistency target of 100 mm slump. The actual slump test results displayed in Table 3.5 are all above 100 mm.

Table 4.5: Recycled Coarse Aggregate Specifications

Sample	Casting Date	Slump (mm)
Control R0	Tuesday 28/01/2014	120
R1(20%R)	Monday 03/02/2014	90
R2(40%R)	Thursday 27/03/2014	110
R3(60%R)	Monday 17/02/2014	120
R4(80%R)	Tuesday 18/02/2014	110
R5(100%R)	Thursday 27/03/2014	160

2. Hardened Properties

The results of the 36 compressive strength tests are shown in Table 3.6. The average strength values for each of the three ages for the six mixes are listed in Table 3.7 and displayed in Figure 3.9.

Table 4.6: Recycled Coarse Aggregate Specifications

		Cylinders compressive strength (Mpa)					
Sample	Casting Date	3 days	Results	7 days	Results	28 days	Results
Control R0	Tuesday 28/01/2014	Friday 31/01/2014	15.6	Tuesday 04/02/2014	21.1	Tuesday 25/02/2014	33.6
			16.1		20.6		34.6
R1(20%R)	Monday 03/02/2014	Thursday 06/02/2014	12.1	Monday 10/02/2014	18.6	Monday 03/03/2014	31.6
			13.2		19.7		30.9
R2(40%R)	Thursday 27/03/2014	Monday 31/03/2014	11.775	Thursday 03/04/2014	19.4	Thursday 24/04/2014	31.2
			12.525		19.6		31.6
R3(60%R)	Monday 17/02/2014	Friday 21/02/2014	11.1	Monday 24/02/2014	19.2	Monday 17/03/2014	31.3
			11.55		20.3		31.8
R4(40%R)	Thursday 27/03/2014	Monday 31/03/2014	11.775	Thursday 03/04/2014	19.4	Thursday 24/04/2014	31.2
			12.525		19.6		31.6
R5(100%R)	Thursday 27/03/2014	Monday 31/03/2014	12.225	Thursday 03/04/2014	18.9	Thursday 24/04/2014	29.4
			12.75		19.5		30.2

Table 4.7: Recycled Coarse Aggregate Specifications

			28 days average strength	
Sample	Average 3 days (MPa)	Average 7 days (MPa)	Value (Mpa)	% Reduction reference to the control mix
Control R0	15.85	20.85	34.1	-
R1(20%R)	12.65	19.15	31.25	8.36
R2(40%R)	12.15	19.5	31.4	7.92
R3(60%R)	11.325	19.75	31.55	7.48
R4(80%R)	11.8	19.45	29.8	12.61
R5(100%R)	12.4875	19.2	29.8	12.61

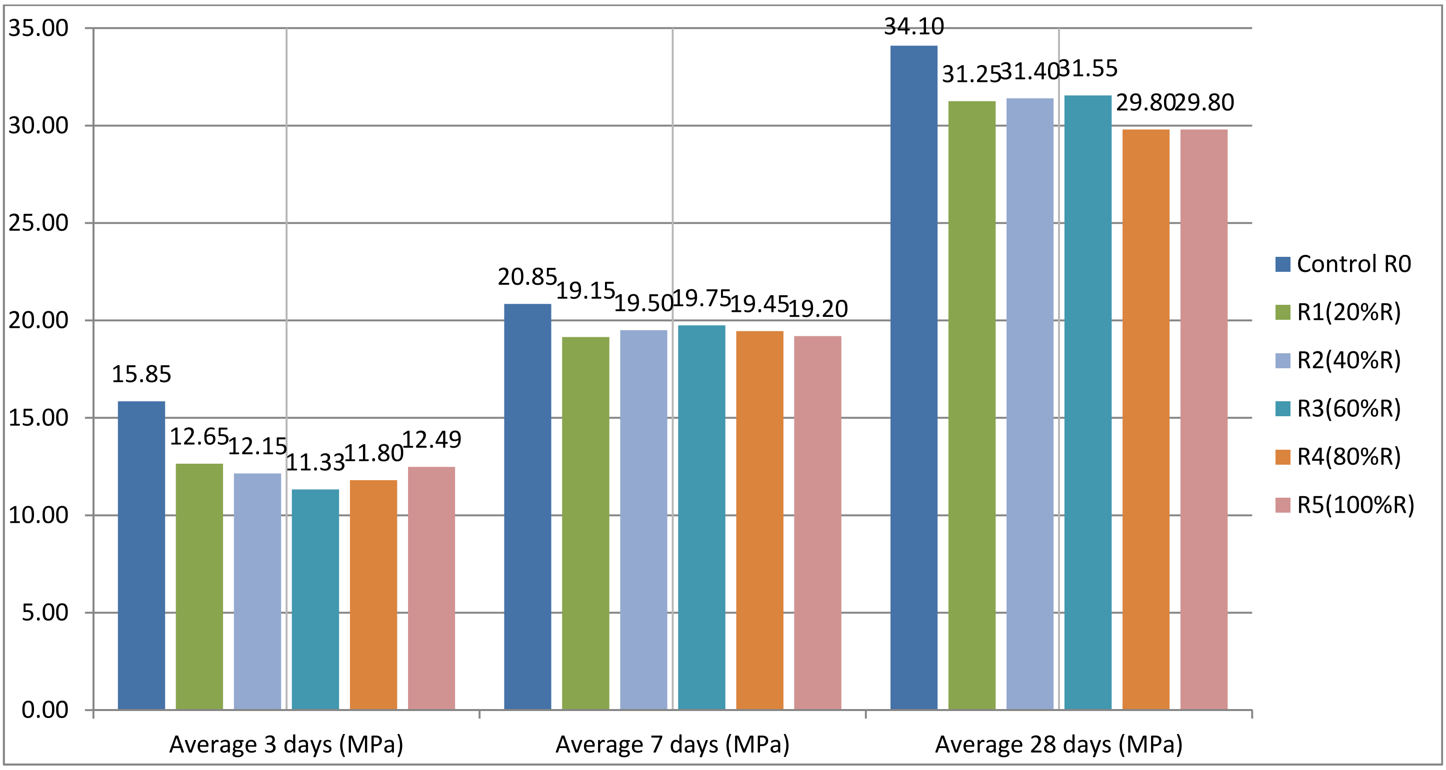

Figure 7-3: Histogram showing average strengths at different ages

Results of the 12 splitting tensile strength tests are shown in Table 3.8.

Table 4.8: Recycled Coarse Aggregate Specifications

				Average splitting strength	
Sample	Casting Date	Test date	Splitting tensile strength (KN)	Value (KN)	% Reduction reference to the control mix
Control R0	Tuesday 25/02/2014	Tuesday 25/03/2014	235.84	229.04	-
			222.24		
R1(20%R)	Monday 03/02/2014	Monday 03/03/2014	200.01	193.31	15.60
			186.60		
R2(40%R)	Thursday 27/03/2014	Thursday 24/04/2014	218.61	209.99	8.32
			201.37		
R3(60%R)	Monday 17/02/2014	Monday 17/03/2014	185.95	190.49	16.83
			195.03		
R4(80%R)	Tuesday 18/02/2014	Tuesday 18/03/2014	198.65	198.20	13.47
			197.75		
R5(100%R)	Thursday 27/03/2014	Thursday 24/04/2014	197.75	199.11	13.07
			200.47		

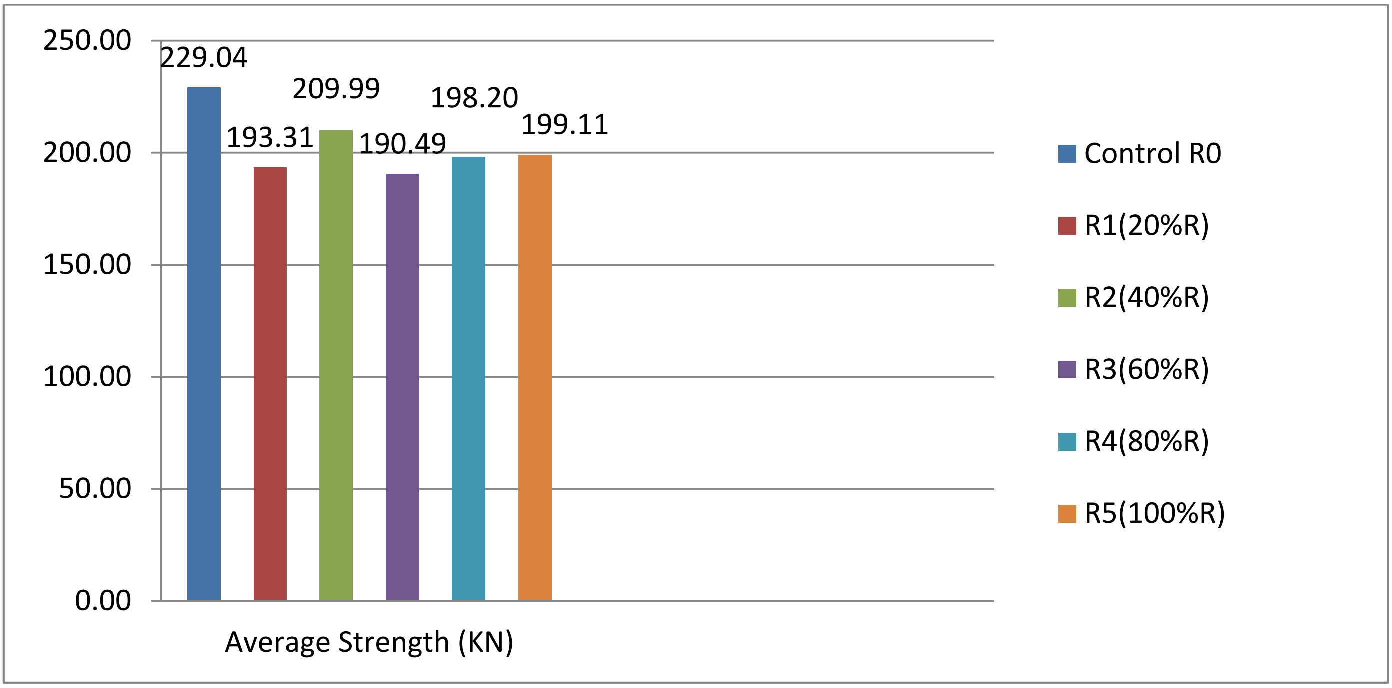

Figure 7-4: Histogram showing average splitting strength

Table 4.9: Recycled Coarse Aggregate Specifications

				Average flexural strength	
Sample	Casting Date	Flexural test date	Flexural strength (KN)	Value (KN)	% Reduction reference to the control mix
Control R0	Tuesday 25/02/2014	Tuesday 25/03/2014	37.42	33.90	-
			30.39		
R1(20%R)	Monday 03/02/2014	Monday 03/03/2014	29.75	31.09	8.29
			32.43		
R2(40%R)	Thursday 27/03/2014	Thursday 24/04/2014	29.25	30.95	8.70
			32.66		
R3(60%R)	Monday 17/02/2014	Monday 17/03/2014	32.20	30.10	11.21
			28.00		
R4(80%R)	Tuesday 18/02/2014	Tuesday 18/03/2014	31.98	30.64	9.63
			29.30		
R5(100%R)	Thursday 27/03/2014	Thursday 24/04/2014	32.20	31.08	8.34
			34.20		

G. Analysis and Discussion

Experimental tests conducted on concrete mixes made using different percentage replacements of natural coarse aggregates with recycled coarse aggregates revealed the following:

Replacement of NCA with different percentage of RCA had no negative impact on consistency of the concrete mix. The slump values for five mixes ranged between 90 and 120 mm. the mix with 100% Rpl had a 160 mm slump.

The replacement of different percentages of NCA with RCA led to an average reduction of 9.8% in the ultimate compressive strength, an average reduction of 13.46% in the tensile splitting strength and an average reduction of 9.23% in the flexural strength. The average reductions in the compressive and flexural strengths were comparable. The reduction in the splitting tensile strength was greater. There was no significant difference in the strength values related to the RPL of NCA by RCA with the exception of the 40% replacement. Where the reduction in the splitting tensile strength relative to the control value was 8.32% whereas other percentage replacements led to reductions ranging from 13.07 to 16.83%

All the previously mentioned results lead to a conclusion that the performance of RAC both in fresh and hardened conditions is highly similar to the performance of natural concrete. No significant alerting difference in results was observed. All properties were in an acceptable range of difference from those of natural concrete.

CHAPTER V

PHASE II: EFFECT OF RECYCLED AGGRETGATES ON STRUCTURAL BEHAVIOR OF REINFORCED - CONCRETE BEAMS

A. Introduction

Analysis of the experimental results of Phase I led to a conclusion that different percentages of replacement of the natural coarse aggregates with recycled aggregates from concrete cylinders, led to similar effect on the fresh and hardened properties of concrete. Whereas there was no significant effect on the consistency or slump of the different concretes, the reduction in the compressive and tensile strengths of standard 6x12 in (150x300 mm) cylinders was around 15 %. Also the reduction in the flexural strength and modulus of elasticity was on the average of 15 %. Given the conclusion of Phase I, two replacement percentages were chosen in this second phase to cover an average replacement percentage of 40 % and a total replacement percentage of 100 %.

The second phase of the research program was designed to assess the structural behavior of reinforced concrete beams prepared by replacing the natural coarse aggregates with different percentages of recycled aggregates from tested concrete cylinders. A total of 18 full-scale normal strength concrete (NSC) simply supported beam specimens were tested. The nominal concrete strength used in all beams was 20 MPa. The first variable was the percentage replacement of NCA with RCA [0(control), 40, or 100%]. The second variable was the mode of failure of the tested beams (flexure, shear, or bond splitting). For each of the three percentage replacement two replicate beams were tested to fail in flexure, two to fail in shear, and two beams were tested to fail in bond splitting of the concrete cover in the splice region. Each flexural beam was reinforced with two main bars and adequate stirrups or shear reinforcement to avoid shear failure. Each shear beam was reinforced with two main bars but was under-designed in shear to induce shear failure. Each bond beam was reinforced with two bars on the tension side spliced in a constant moment region at mid-span. The splice length was chosen in such a way that the beams would fail in bond splitting of the concrete cover in the splice region. Replicates were used to validate the test results.

At each load increment, deflections at mid-span were recorded and flexural cracks outside and inside the splice region were marked. The effect of RAC for each failure mode was evaluated by comparing the performance of the companion specimens with different percentage replacement. Comparison is based on the mode of failure, ultimate load, and general load-deflection behavior.

The following sections present detailed descriptions of the experimental program that has been adopted, the design criteria and the testing methodologies that were followed, and a detailed analysis of the testing outcomes.

B. Experimental Program

1. Variables and Specimen Design

The eighteen beams tested in Phase II of the research program are identified in Table 4.1. The beams are devided into three sets, each with a different mode of failure.

The beams are identified by a four part notation system. The first term indicates the concrete strength of the mix used in the casting of the beam (N for normal strength). The second term specifies the preset mode of failure (F for flexure, S for shear, and B for bond splitting). The third term designates the type of concrete mix used in casting the beam specimen (N for natural aggregates with 0 percentage replacement, 40 for RAC 40 percent replacement, and 100 for RAC 100 percent replacement). The forth term designates the listing number of the two replicates (1 or 2).

The beams were tested in positive bending. The loading system was designed to produce a constant moment region in the middle of the beam specimen. The beam specimen was 2000 mm long with a distance of 1800 mm between supports. The distance between the two applied loads was 600 mm. The width of the beam was 200 mm and the depth was 300 mm. Longitudinal and cross sectional details is shown in Figures 5.1, 5.2, and 5.3.

Table 5.1: Variables of Phase II

Beam Name	Beam Notation	Concrete Mix	Mode of Failure
Flexural Beams	N-F-N-1	Natural	Flexure
	N-F-N-2	Natural	Flexure
	N-F-40-1	RAC 40	Flexure
	N-F-40-2	RAC 40	Flexure
	N-F-100-2	RAC 100	Flexure
	N-F-100-2	RAC 100	Flexure
Shear Beams	N-S-N-1	Natural	Shear
	N-S-N-2	Natural	Shear
	N-S-40-1	RAC 40	Shear
	N-S-40-2	RAC 40	Shear
	N-S-100-2	RAC 100	Shear
	N-S-100-2	RAC 100	Shear
Bond Beams	N-B-N-1	Natural	Bond Splitting
	N-B-N-2	Natural	Bond Splitting
	N-B-40-1	RAC 40	Bond Splitting
	N-B-40-2	RAC 40	Bond Splitting
	N-B-100-2	RAC 100	Bond Splitting
	N-B-100-2	RAC 100	Bond Splitting

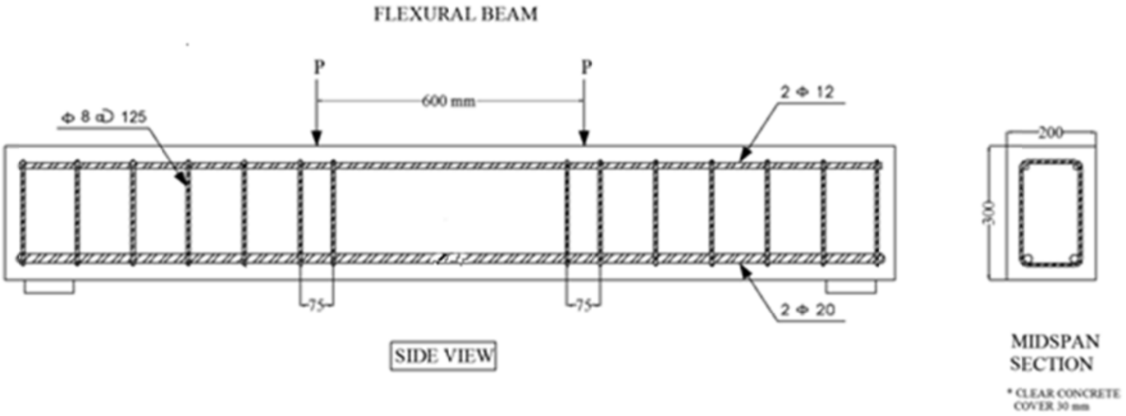

Figure 8-1: Flexural Beams - Reinforcement Details; all dimensions are in mm.

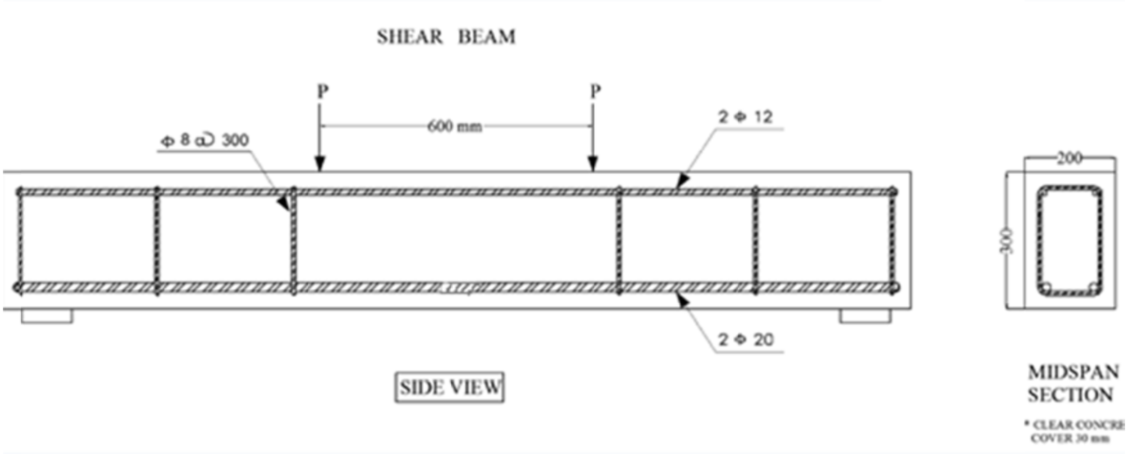

Figure 8-2: Shear Beams - Reinforcement Details; all dimensions are in mm.

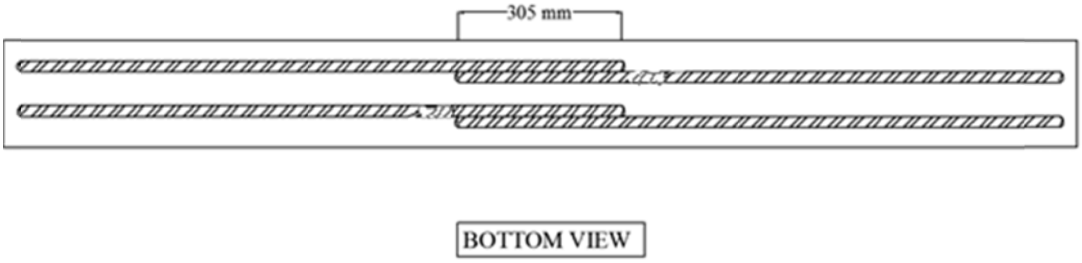

Figure 8-3: Bond Beams - Reinforcement Details; all dimensions are in mm.

2. *Constituent materials*

a. Concrete

The mix design adopted in Phase I of the experimental program was again used in this Phase II.

All eighteen beams were cast on the same day. One batch was used for each set of six beams. All specimens were cast at the ARACO local batching plant using their batching machines and systems.

Standard 150x300 mm (6x12 in.) cylinders were taken from the different concrete batches at the ready mix plant to be tested to determine the concrete compressive strength f’$_c$. View of the recycled material and the source of natural material is shown in Figure 5.4

Figure 8-4: Recycled aggregates kept in piles of two sizes separately

b. Steel Reinforcement

The reinforcement of each beam consisted of two longitudinal 20 mm reinforcing bars on the tension side and two 12 mm reinforcing bars on the compression side. Stirrups, 8 mm in diameter, were provided in the shear regions. All bars were Grade 60 satisfying ASTM A615M.

3. *Specimen Construction*

a. Formwork

The forms, made of marine plywood, were manufactured to have inner dimensions of 200x300x2000 mm. All eighteen beams were manufactured side to side in order to maximize lateral stiffness for the formwork sides. View of the formwork with the installed steel cages is shown in Figure 5.5

Plastic concrete spacers between the steel cages and the form sides were used to guarantee side and bottom covers of 30 mm. Because of the absence of stirrups in the middle third of the beam and to avoid the usage of spacers at the constant moment region under study, the top reinforcement was wired to the top bracers to fix the steel cage and to prevent sagging of the longitudinal reinforcement during transportation and casting.

Figure 8-5: Assembled Formwork for set of six beams

Figure 8-6: Steel Cages in formwork with plastic spacers

b. Steel Cages

Three types of steel cages were prepared based on the structural design requirements and the tested mode of failure. The bottom and top rebars were cut to ensure a 30 mm clear concrete cover at the ends of the beam. In the bond beams, the bottom reinforcing bars were spliced 305 mm (12 in.) at the middle of the beam.

Concerning shear reinforcement, the closed hoop stirrups were also dimensioned taking into account a design concrete cover of 30 mm on the 4 sides. With reference to the ACI building code ACI 318-12, a minimum inside bend diameter of 4 d_b was adopted for the stirrups with a minimum extension length of 50 mm at the free end of the bar, equivalent to 6 d_b.

View of the steel cages is shown in Figure 5.7

Figure 8-7: Steel Cages

c. Placement Method

The control beams (N beams) and the recycled aggregate concrete beams were poured at the ready mix plant during the same day. One batch was used for each set of six beams of a given concrete mix. The material was mixed in the batching machine used by the ready mix plant for regular concrete production.

The control Natural concrete beams were placed first. The results of the Abram's cone test revealed a concrete slump of 140 mm. A vibrator was used to help the concrete to spread evenly inside the forms. Cylinders were taken to test for compressive strength of concrete.

The 40 % and 100 % replacement beams were then poured with a slump flow of 130 mm and 155 mm respectively. Similar vibrating technique was used to help concrete spread evenly inside in the forms.

Refer to Figure 5.8 to 5.15 for casting procedure.

Figure 8-8: Roller belt carrying material

Figure 8-9: Batching plant

Figure 8-10: Concrete sampling

Figure 8-11: Preparing cylinders for testing the compressive strength

Figure 8-12: Cylinders for testing

Figure 8-13: Concrete pouring

Figure 8-14: Concrete pouring and spreading

Figure 8-15: Concrete consolidation by vibrator

d. Curing Method

The sides of the beams wooden forms were stripped off three days after casting. The three days aged concrete beam specimens were entirely covered by wet burlaps. Water was sprayed in the morning and the evening to preserve moisture until the concrete attained the age of 28 days. Identical curing methods were adopted for the 150 x 300 mm (6x12 in) cast cylinders. All the specimens were transported to the Civil Engineering Materials Laboratory at AUB at an age of 28 days for testing.

4. *Testing Procedure*

The reinforced concrete beams were tested using an MTS machine. The span between the centerlines of the supports was taken to be 1800 mm. Two concentrated loads were applied continuously at a distance from the two supports equivalent to one third of the span length (600 mm). The vertical deflection was monitored at mid-span using an LVDT sensor. The loads were applied in increments of 10 kN until failure. At each load increment, cracks were marked and their extensions were traced. In the flexural and shear beams, cracks that initiated below the two concentrated loads and at mid-span were observed. In the bond beams, cracks located at the end of the lap splices were also checked. In all beams, the propagation of the shear cracks was examined attentively.

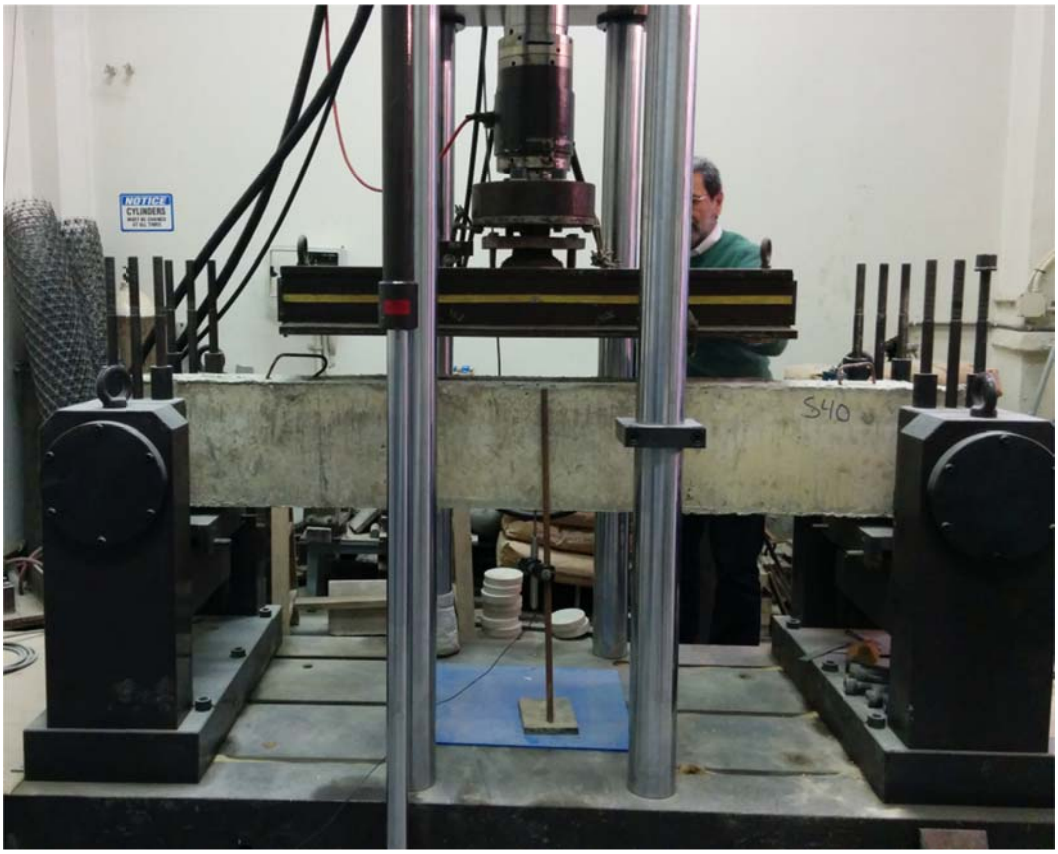

Figure 8-16: View of the test setup

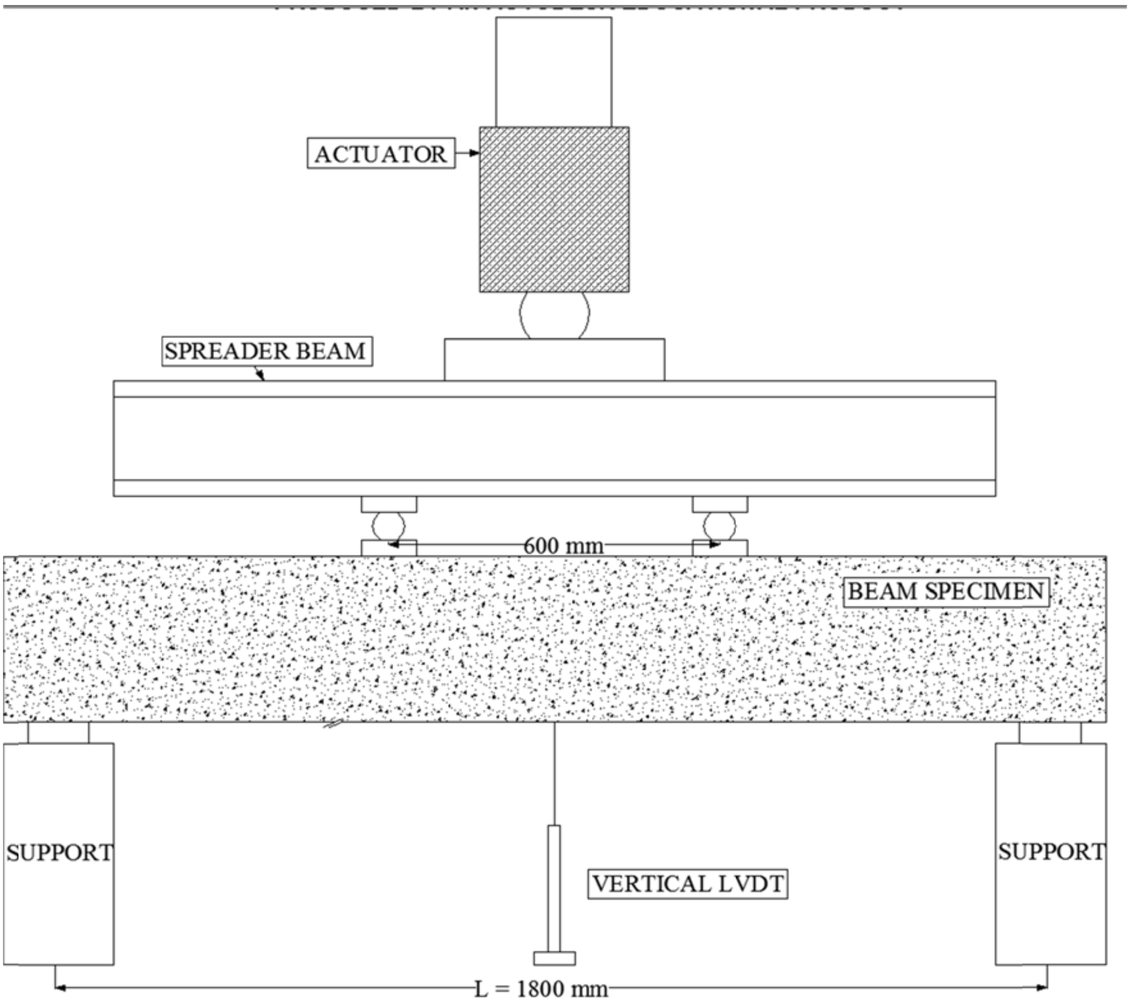

Figure 8-17: Schematic of the test setup

C. Beam Specimen Behavior and Analysis of Results

In the following sections, the behavior of the eighteen beam specimens cast using RAC and natural aggregate concrete mixes will be discussed and test results will be presented and analyzed. Summary of test results of all eighteen beams is presented in Table 5.6. The listed data includes the ultimate load reached and the corresponding mid-span deflection.

Table 5.2: Ultimate Loads and Maximum Deflections at Failure

Beam Name	Beam Notation	Pmax (kN)	Δ_{max} (mm)
Flexural Beams	N-F-N-1	199.2	7.1
	N-F-N-2	194.3	8.2
	N-F-40-1	204.2	9.1
	N-F-40-2	223.1	9.4
	N-F-100-2	240.8	11.5
	N-F-100-2	213.6	12.1
Shear Beams	N-S-N-1	155.2	6.1
	N-S-N-2	170.5	7.5
	N-S-40-1	159.1	7.3
	N-S-40-2	166.58	6.8
	N-S-100-2	158.38	8.5
	N-S-100-2	160.18	7.8
Bond Beams	N-B-N-1	118.1	4.3
	N-B-N-2	120.2	4.5
	N-B-40-1	140.6	3.8
	N-B-40-2	135.2	4.2
	N-B-100-2	120.2	5.16
	N-B-100-2	122.2	5.26

1. Flexural Beams

The mode of failure of the flexural beams can be described as follows. The first crack initiated in the tension zone when the stress reached the concrete tensile capacity. As the load was increased, the cracks developed along the entire beam width, and other cracks initiated in the shear zone (near supports). Finally, failure occurred when the shear capacity was reached. Failure was anticipated by multiple cracks that developed near the support on the left or right side.

a. Crack Patterns

View of three cracked flexural beams is shown in Figure 5.18. The figure shows the crack patterns of the control (N beams), 40% replacement beam and the 100 % replacement beam.

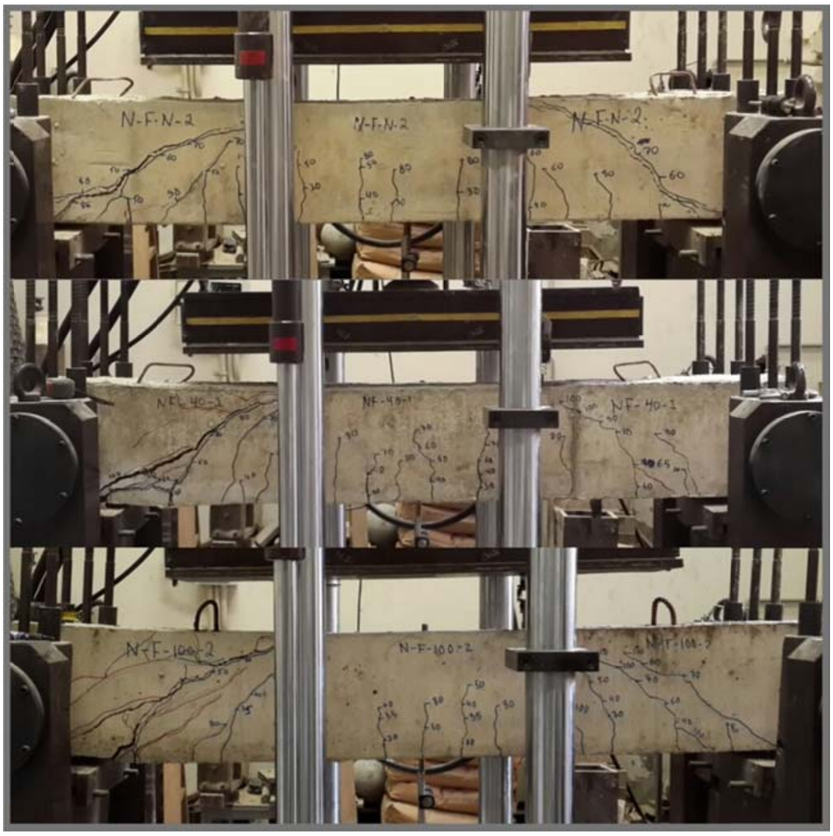

Figure 8-18: Cracked Flexural Beams

Along with the fact that the crack patterns were similar for the control, 40% and 100 % flexural beams, also the first flexural crack occurred for all flexural beams at a load of approximately 30 kN. The results indicate similar tensile capacity of the control, 40% and 100% flexural beams when subject to bending. Flexural cracks in the loading region at the flexural beam's mid-span stopped propagation vertically after the load of 50 kN. Approaching the load at failure, minor propagations of such cracks occurred similarly in all three flexural beams.

The load at first diagonal crack for the three flexural beams was between 50 and 60 kN. The propagation of these diagonal shear cracks at supports was similar in terms of starting point, angle of propagation and crack width. All these factors were monitored visually.

The maximum load P was related to the appearance of the first diagonal crack marks the critical load beyond which concrete fails to resist additional tensile stresses perpendicular to the shear plane of failure.

The crack at the failure load for all three flexural beams propagated from one side of a support at an angle of approximately 45 degrees reaching the top surface of the beam.

b. Load-Deflection Test Results

Although the concrete compressive strength of the 40% and 100% flexural beams was less by 10-15% as compared to the control mix, the maximum flexural loads of the 40% and 100% specimens were comparable to that of the control beam and even with a higher value. The average maximum flexural load was 195 kN for the control beams, 210 kN for the 40% beams, and 226.5 kN for the 100% beams. Thus, the 40% and 100% RAC mixes resulted in a maximum flexural load comparable and even higher than to the control beam while replacing natural coarse aggregates with recycled coarse aggregates up to 100 percent.

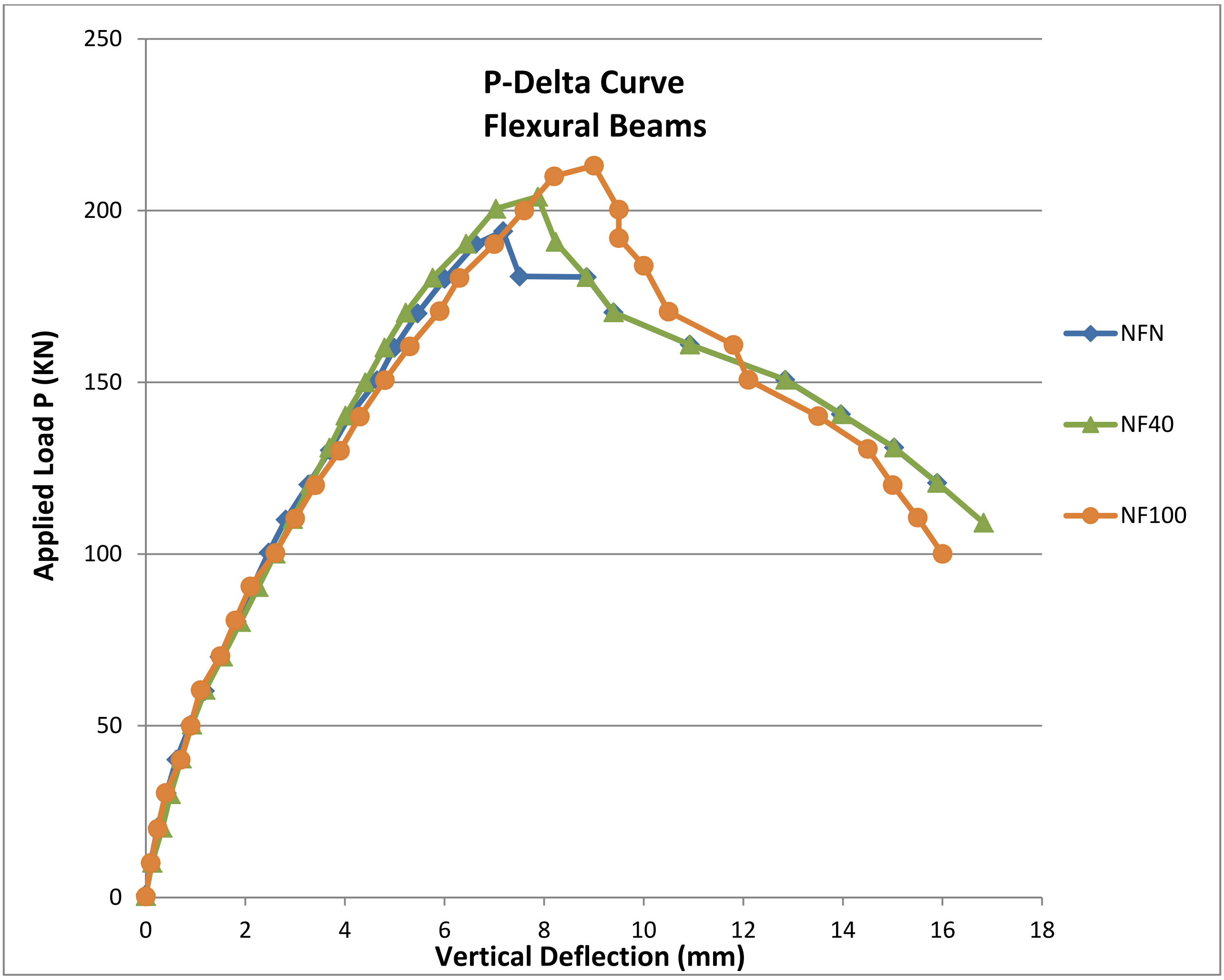

Figure 8-19: Load-Deflection Curves for Flexure Beams

To evaluate the effect of RAC on toughness and ductility of the flexural beam specimens, the area under the load-deflection curve was used as an indicator. The area under the load-deflection curve was calculated for a deflection range between zero and 20 mm. The values were 8593, 8828 and 8890 kN-mm for the control, the 40% and the 100% replacement flexural beams, respectively. It is obvious that although the 100% replacement flexural beam has the largest area, however the values are very close and differ within a range of 5%.

2. *Shear Beams*

Similar to the flexure beam specimens, the first crack initiated in the tension zone. However, failure occurred in the shear zone, because the beams are under-designed for shear. Failure was anticipated by the shear cracks that developed near the support on the left or right side, in the shear zone.

a. Crack Patterns

View of three cracked shear beams is shown in Figure 5.20. The figure shows the crack patterns of the control (N beams), 40% replacement beam and the 100 % replacement beam.

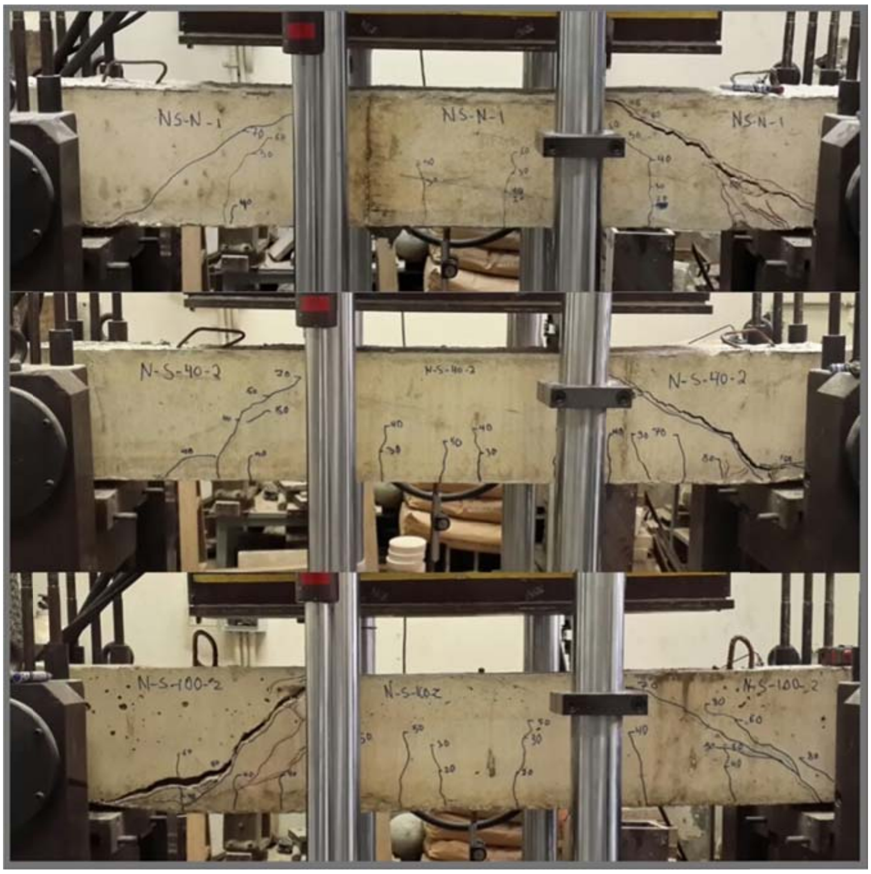

Figure 8-20: Cracked Shear Beams

Similar to the flexural beams the crack patterns were similar for the control, 40% and 100 % shear beams. The first flexural crack occurred for the control, the 40% and the 100% shear beams at loads of approximately 20, 30 and 20 kN respectively. The results indicate similar tensile capacity of the control, 40% and 100% flexural beams when subject to bending. The flexural cracks in the loading region at the shear beam’s mid-span stopped propagation vertically after the load of 50 kN for the control and 100% shear beams and at a load of 40 kN for the 40% shear beam. Approaching the load at failure, no further propagations of such cracks occurred similarly in all three shear beams. The number of developed flexural cracks in these shear beams is smaller than I the flexural beams.

The load at first diagonal crack for the three flexural beams was between 50 and 60 kN. Similarly to the flexural beams, the propagation of these diagonal shear cracks at supports was similar in terms of starting point, angle of propagation and crack width. All these factors were monitored visually. .

The shear crack at the failure load for all three flexural beams propagated from one side of a support at an angle of approximately 45 degrees reaching the top surface of the beam.

b. Load-Deflection Test Results

Although the concrete compressive strength of the 40% and the 100% replacement flexural beams was less by 10-15% as compared with the control mix, the ultimate loads of the 40% and the 100% specimens were comparable to that of the control beam. The average maximum load was 162.5 kN for the control shear beams, 163.0 kN for the 40% beams, and 159.5 kN for the 100% beams. Thus, the 40% and 100% RAC mixes resulted in a maximum load for the shear beams comparable to the natural control shear beam with a difference of less 2%. All shear beams had a sharp drop in load after ultimate indicating brittle behavior.

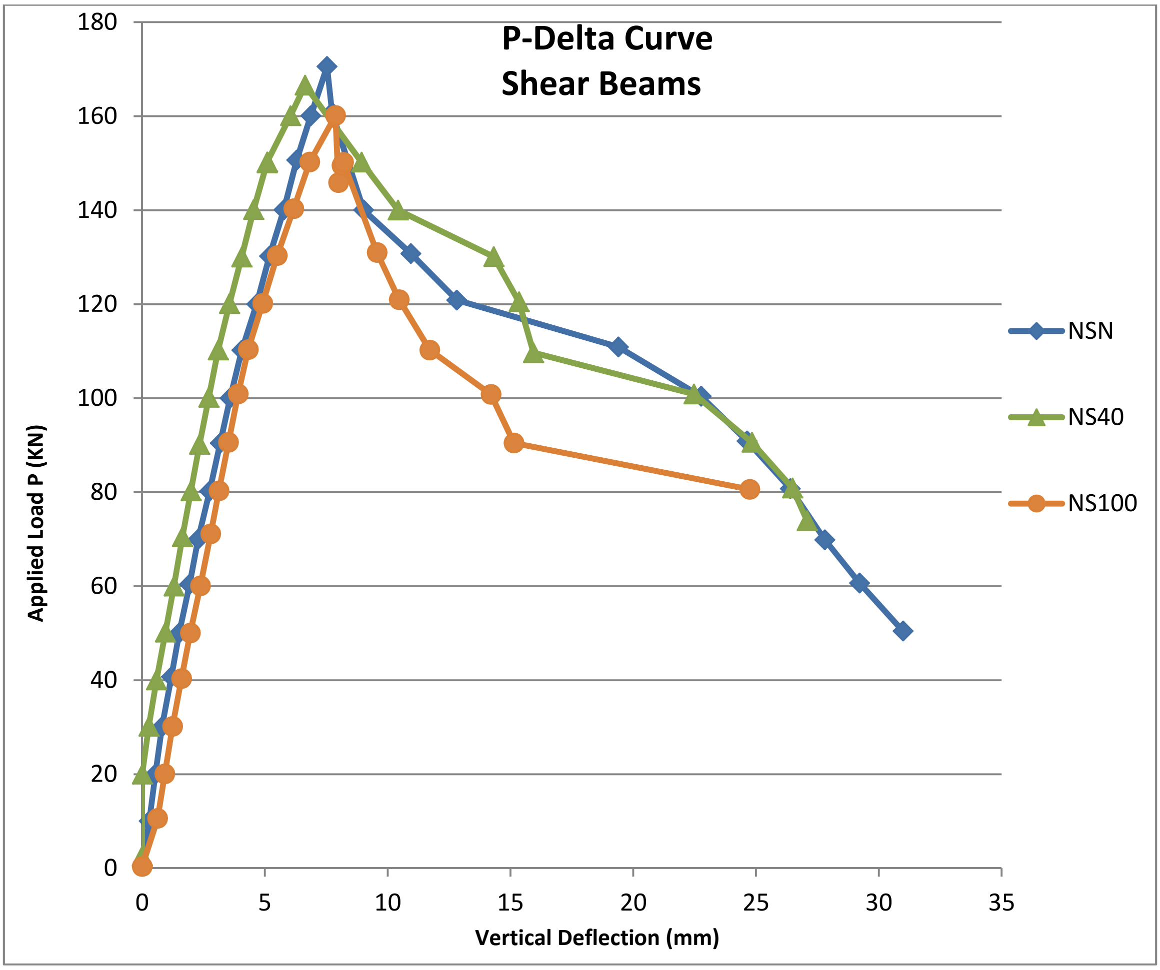

Figure 8-21: Load-Deflection Curves for Flexure Beams

3. Bond Beams

For the beam specimens set to fail in the bond splitting mode, closer attention was made to the region of splice. The failure was anticipated to happen in that region after the formation of splitting cracks.

a. Crack Patterns

View of three cracked bond beams is shown in Figure 5.22. The figure shows the crack patterns of the control (N beams), 40% replacement beam and the 100 % replacement beam.

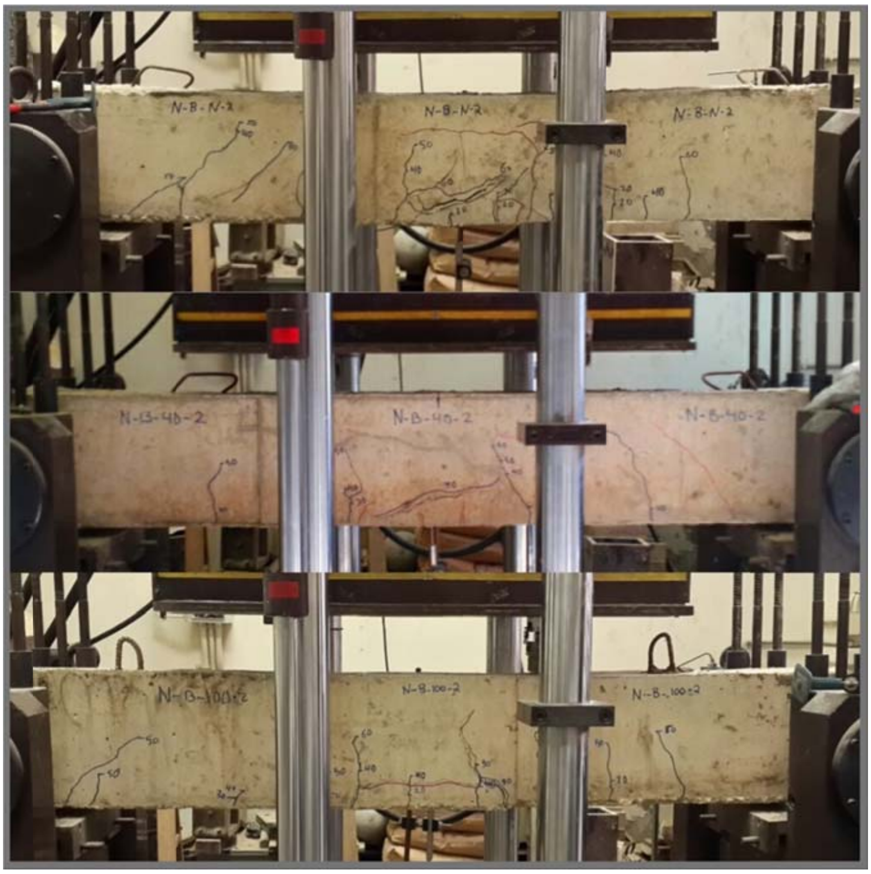

Figure 8-22: Cracked Shear Beams

Similar to the flexural and shear beams the crack patterns were similar for the control, 40% and 100 % bond beams. The first flexural crack occurred for the control, the 40% and the 100% shear beams at a load of approximately 20, 30 and 20 kN, respectively. The results indicate similar tensile capacity of the control, 40% and 100% bond beams when subject to bending.

The load at first diagonal crack for the three flexural beams was between 40 and 50 kN. The propagation of these diagonal shear cracks at supports did not continue beyond this value.

As mentioned, the first cracks initiated in the tension zone, similar to the flexural and shear beams, yet failure occurred along the mid-span where the provided splices length 30.5 cm (12 in) was less than the required design length. Failure splitting cracks were observed at the bottom side in the splice region. The bond splitting crack propagated along the splice on the tension face of the beam as shown in Figure 5.23.

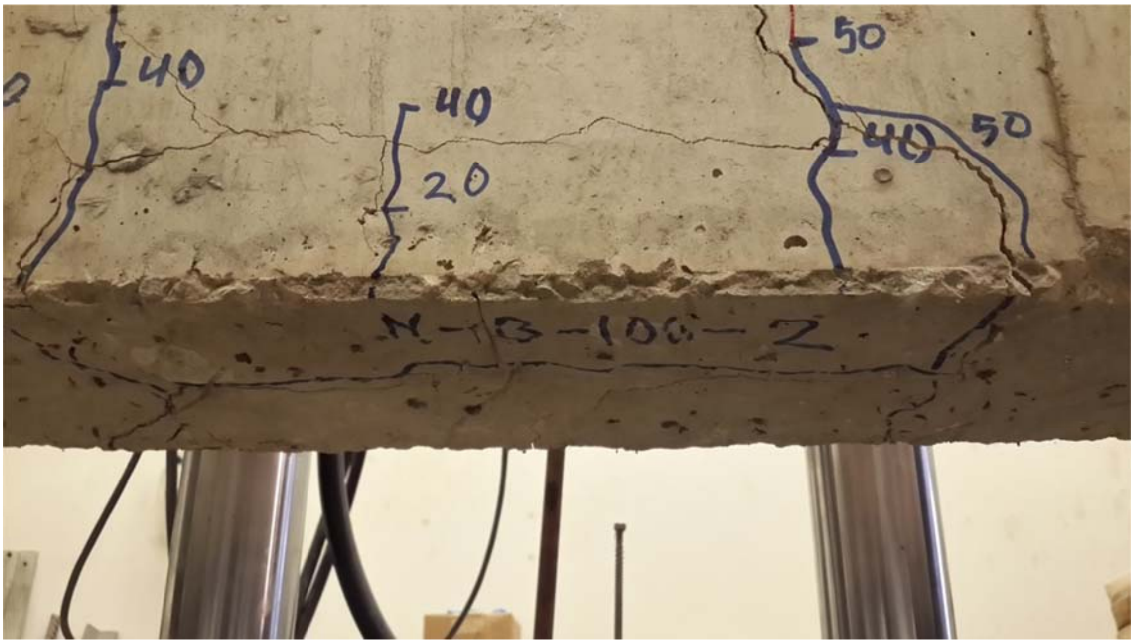

Figure 8-23: Splitting cracks in 100 % bond beams

b. Load-Deflection Behavior

Although the concrete compressive strength of the 40% and 100% flexural beams was less by 10-15% as compared with the control mix, the maximum loads of the 40% and 100% specimens were comparable to that of the control beam. The average maximum load was 119.0 kN for the control shear beams, 137.5 kN for the 40% beams, and 121.2 kN for the 100% beams. Thus, the 40% and 100% RAC mixes resulted in a maximum load for the bond beams comparable to the natural control bond beam. Similar to the shear beams, all bond beams had a sharp drop in load after ultimate indicating brittle behavior.

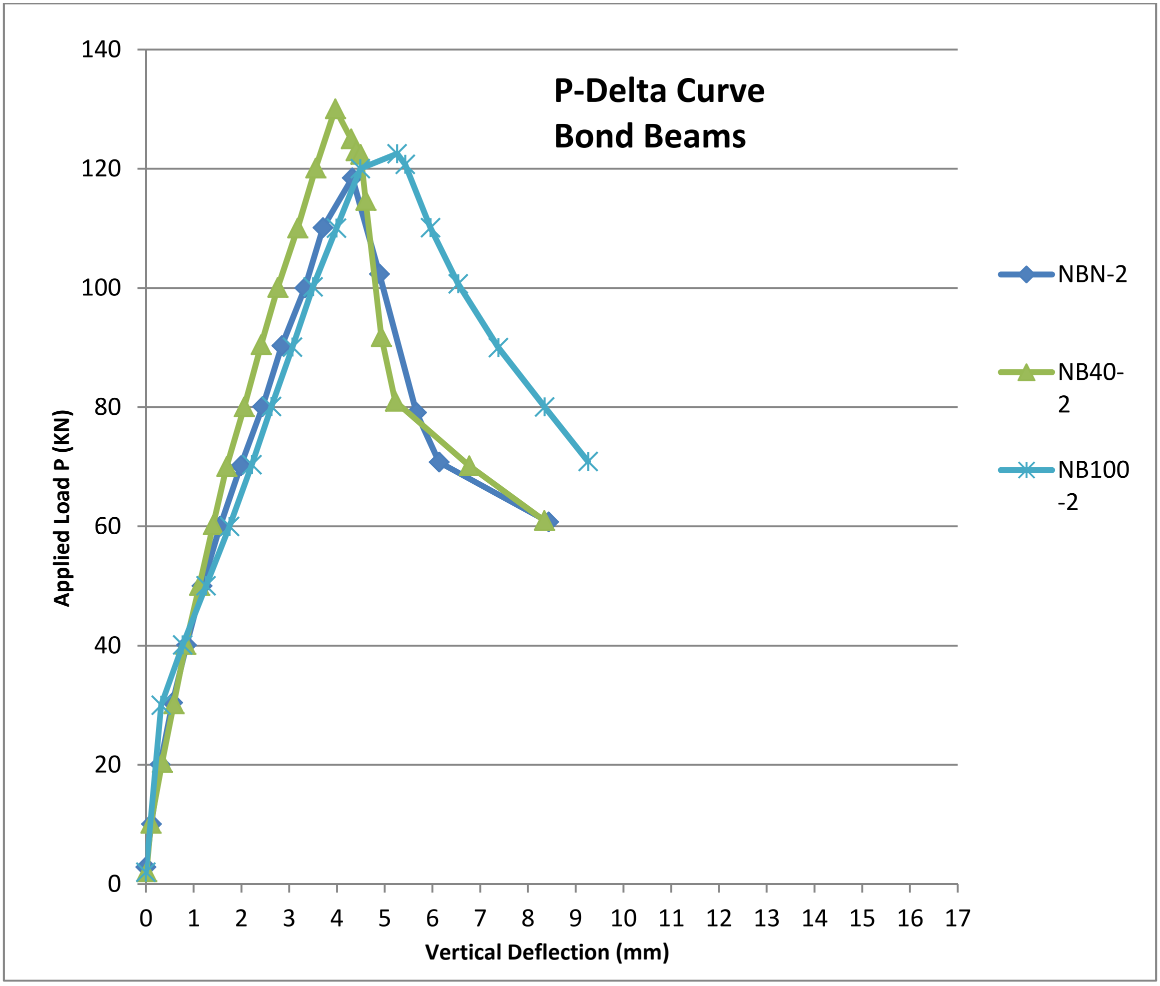

Figure 8-24: Load-Deflection Curves for Flexure Beams

CHAPTER VI

CONCLUSIONS & RECOMMENDATIONS

A. Research Summary

A two-phase research program was conducted to study the applicability of replacing part or all of the natural crushed limestone coarse aggregates (NCA) in a normal strength concrete (NSC) mix with recycled coarse aggregates (RCA) which resulted from tested and crushed concrete cylinders, major waste product of the concrete construction industry.

Regardless of the findings of the research program, recycling tested concrete cylinders reduces the negative environmental impact of limestone quarries, reduces the depletion of natural recourses, reuses the waste products of the concrete production industry in concrete production and reduces the amount of waste correlated with this industry.

The main objective was to assess the effect of percentage replacement of natural coarse aggregates (NCA) with recycled coarse aggregates (RCA) on the structural behavior of structural NSC beam elements designed to fail in different critical modes of failure.

The lack of expertise knowledge available in the local concrete industry and the scarcity of research literature dealing with the effect of natural coarse aggregate (NCA) replacement with recycled coarse aggregates (RCA) in normal strength concrete (NSC) on the flexural, shear and bond capacities of reinforced concrete beams, placed additional challenges to meet the predefined objective. The experimental work was subdivided into two interrelated phases of equal importance:

Phase I

Extensive testing was performed on different normal strength concrete mixes that had different percentage replacements of NCA with RCA [0 (control), 20, 40, 60, 80 and 100 percent]. Physical properties of fresh concrete mixes and hardened concrete cylinders and standard beams were tested and compared.

Phase II

The flexural, shear, and bond splitting strength of reinforced structural beams cast with three different percentage replacements of NCA with RCA [0 (control), 40, and 100 percent] were assessed. For each of the three modes of failure, three beams with different percentages replacement were tested. One replicate was prepared for each beam to validate the test results. A total of 18 beams were tested. The loading system produced a constant moment region at mid-span of the beam. Deflections were recorded at mid-span and flexural cracks were traced and marked at load increments of 20 kN.

B. Research Conclusions

The replacement of NCA with different percentages of RCA did not have a negative effect on the consistency of fresh concrete. As for hardened the concrete properties, average reductions of 9.8%, 13.46% and 9.23% were recorded in the ultimate compressive strength, splitting tensile strength and flexural strength, respectively. The reductions were not affected by the percentage replacement.

The strength reduction that was noted in the findings of Phase I of the research did not have a negative impact on the structural behavior of reinforced concrete beams prepared by replacing portion or all of the natural coarse aggregates with recycled coarse aggregates. There was no significant difference in the ultimate load reached or load-deflection behavior of beams tested to fail in flexural or shear or bond splitting of the concrete cover in the splice region that could be related to the percentage replacement of NCA with RCA.

Results of the research program have a positive impact on the usage of RCA, produced by crushing tested concrete cylinders, in the concrete construction industry.

C. Economic Feasibility of the Usage of RCA in the Concrete Construction Industry.

Regardless of the findings of the research program, recycling tested concrete cylinders reduces the negative environmental impact of lime stone quarries, reduces the depletion of natural recourses, reuses the waste products of the concrete production industry in concrete production and reduces the amount of waste correlated with this industry, a big question is raised concerning the economic feasibility of the processing of the tested concrete cylinders to produce acceptable recycled aggregates.

A brief cost comparison analysis of the cost of producing one cubic meter of normal strength concrete using natural crushed limestone coarse aggregates to the cost of producing one cubic meter of normal strength concrete with 100% replacement of NCA with RCA is presented below:

1- The amount of cement and fine aggregates is the same.
2- Thirty five additional kilograms of water are required to produce one cubic meter of NSC with 100% replacement of NCA with RCA due to higher absorption capacity of RCA.

3- As compared to the cost of producing the natural crushed limestone rocks in the natural quarries, there is no cost buying the tested concrete cylinders since they are a waste material at the batching plant.

4- The cost of crushing the natural limestone rocks in the natural quarries to the needed coarse aggregates size and sieving the products to the required standard ASTM requirements is assumed to be comparable to the cost of crushing the tested concrete cylinders and sieving the resulting recycled aggregates to the required standard sizes. Add to the above cutting the cost of collecting, transporting, and dumping the tested cylinders as waste material.

It could be concluded that savings in the concrete construction industry are generated by replacing different portions of NCA by RCA.

D. Future Research

The two-phase research work presented in this thesis document recommends that further research work shall be made in the following fields:

1) Durability of RAC elements due to different exposures.
2) The applicability of the research’s results on high strength concrete

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