COMPRESSIVE STRENGTH AND BOND BEHAVIOUR OF RECYCLED COARSE AGGREGATE CONCRETE

A Thesis Report submitted in the partial fulfillment of requirement for the award of the degree of

MASTER OF ENGINEERING

IN

STRUCTURES

Submitted By

Shilpa Singla

Roll No. 801122021

Under the Supervision of

DR. SHWETA GOYAL

Assistant Professor,
Department of Civil Engineering
Thapar University, Patiala

DR. NAVEEN KWATRA

Head and Associate Professor,
Department of Civil Engineering
Thapar University, Patiala.

DEPARTMENT OF CIVIL ENGINEERING THAPAR UNIVERSITY,

PATIALA- 147004, (INDIA).

JULY-2013

DECLARATION

I hereby declare that the work which is presented in this thesis report entitled **"Compressive Strength And Bond Behaviour Of Recycled Coarse Aggregate Concrete"**, in partial fulfillment of the requirement for the award of degree of **MASTER OF ENGINEERING (STRUCTURAL ENGINEERING)** in the **CIVIL ENGINEERING DEPARTMENT, THAPAR UNIVERSITY, PATIALA**, is an authentic record of the initial work carried out by her under the supervision of **Dr. Naveen Kwatra, Head and Associate Professor, and Dr. Shweta Goyal, Assistant Professer, DEPARTMENT OF CIVIL ENGINEERING, THAPAR UNIVERSITY, PATIALA.**

The matter embodied in this report has not been submitted in part or full to any other university or institute for the award of any degree.

Date: 15/7/13

Shilpa

(SHILPA SINGLA)

This is to certify that the above declaration made by the student concerned is correct to the best of my knowledge and belief.

15/7/13

(Dr. Shweta Goyal)
Assistant Professor
Deptt. of Civil Engineering,
Thapar University, Patiala

15/7/13

(Dr. Naveen Kwatra)
Head and Associate Professor,
Deptt. of Civil Engineering,
Thapar University, Patiala

Counter Signed by

15/7/13

(Dr. Naveen Kwatra)
Head and Associate Professor,
Deptt. of Civil Engineering,
Thapar University, Patiala

(Dr. S. K. Mohapatra)
Dean Academic Affairs
Thapar University,
Patiala

ACKNOWLEDGEMENT

A dissertation cannot be completed without the help of many peoples who contribute directly or indirectly through there constructive criticism in the evolution and preparation of this work. It would not be fair on my part, if I don't say a word of thanks to all those whose sincere advice made this period a real educative, enlightening, pleasurable and memorable one.

I would like to express my deepest appreciation to my thesis supervisor, Head and Associate Professor **Dr. Naveen Kwatra** and **Dr. Shweta Goyal** for their gracious efforts and keen pursuits, which has remained as a valuable asset for the successful instrument of my Thesis Report. His dynamism and diligent enthusiasm has been highly instrumental in keeping my spirit high. His flawless and forthright suggestions blended with an innate intelligent application have crowned my task a success.

I would also like to express my gratitude to my family, for their unconditional support and prayers at all time and constant encouragement during the entire course of my thesis work.

I am also like to offer my sincere thanks to all faculty, teaching and non-teaching of Civil Engineering (CED) TU, Patiala for their assistance. Thank you.

SHILPA SINGLA

Roll No. 801122021

ABSTRACT

Sustainable resource management and development have been at the forefront of important issues concerning the construction industry for the past several years. Specifically, the use of sustainable building materials and the reuse and recycling of previously used building materials is gaining acceptance and becoming common place in many areas. As one of the most commonly used building materials in the world, concrete, composed of aggregate, sand, cement and water, can be recycled and reused in a variety of applications.

Using crushed concrete as fill and sub-grade material under roads, sidewalks and foundations has been the most common of these applications. However, research has been ongoing over the past 50 years in many countries including Germany, India, Canada, Japan, the United States, China, and Australia investigating the use of crushed concrete from demolished old concrete structures to fully or partially replace the virgin aggregate used to produce new concrete for use in building and pavement applications. Producing concrete using recycled concrete aggregates (RCA) has several advantages, namely, the burden placed on non-renewable aggregate resources may be significantly decreased, the service life and capacity of landfill and waste management facilities can be extended, and the carbon dioxide emissions and traffic congestion associated with the transport of virgin aggregates from remote sites can be reduced.

This research investigates the inter-relationships between aggregate properties, concrete properties and the bond properties between reinforcing steel and RCA concrete.

Forty pullout tests were carried out in order to investigate the bond behaviour between recycled coarse aggregate concrete and steel rebars. Four recycled coarse aggregate (RCA) replacement percentages (i.e., 0%, 30%, 60% and 90%) with water-cement ratio 0.42, 0.45, 0.48, 0.51, 0.55 are considered in this paper. Based on the test results, the influences of both recycled coarse aggregate replacement percentages and water- cement ratio on the bond strength between the recycled coarse aggregate concrete and steel rebars were investigated. It was found that under the equivalent mix proportion (i.e., the mix proportions are the same, except for different recycled coarse aggregate replacement

percentages), the bond strength between the recycled coarse aggregate concrete and rebar initially decreases with an increase of the recycled coarse aggregate replacement percentage, whereas afterwards the bond strength increases with increase in replacement level of coarse aggregate. Bond strength is maximum for 90% replacement level. With the bond strength, compressive strength is also studied and it also shows the same trend as bond strength. A power series relationship exists between compressive strength and bond strength of recycled aggregate concrete. The existing models (ACI 408, Ogura-Koichi model) proposing the square root law underestimates the bond strength of concrete.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

Globally, the concrete industry consumes large quantities of natural resources, which are becoming insufficient to meet increasing demands. At the same time, utility of old structure is diminishing, so these building are demolished to pave way for new and modern construction.Building are demolished due to various reasons i.e. reconstruction for better economic gains, natural disasters and war-inflicted damages. The rate of demolition is increasing day by day and at the same time, the cost of dumpingis increasing due to non-availability of appropriate site nearby. Besides scarcity of land, other problems associated with the landfill option include their silting; transportation cost and public opposition.Thus, recycling has been gaining wider attention as a viable option for handling of waste concrete. One of the materialsthat can be recycled in the demolished structure is coarse aggregate. Utilization of Recycled Aggregate in concrete has been engaged due to awareness of society in natural resources protection. The application of Recycled Aggregate as coarse aggregate in concrete mixes has been initiated so as to make effective use of the waste materials. Figure 1.1 shows how recycled aggregate looks likes.

Figure 1.1: Recycled Aggregate

The use of recycled aggregates in concrete opens a whole new range of possibilities in the reuse of materials in the building industry. The application of recycled aggregates is akeyto the problem of an excess of waste material. The studies on the use of recycled aggregates have been going on for many years, and none of the results showed that recycled aggregates are disagreeable for structural use *(Rakshvir, Barai, 2006)*. However the concrete using Recycled Aggregate (familiarly known as Recycled Aggregate Concrete) has obtained lower performance compared to concrete using Natural Aggregate *(Suraya et al.2011)*

Although there is growing emphasis on the use of recycles coarse aggregate for making new concrete in the West and far Eastern countries like Japan and Korea, there is relatively little awareness of the potential application of such aggregates in India. After China, India is the leading consumer of cement in the world, which by implication means that India is also one of the leading consumers of concrete-making materials like fine and coarse aggregate *(Das et al. 2010)*. Since aggregate sources are not inexhaustible, it is imperative to create awareness about the potential use of recycled coarse aggregate in the manufacture of concrete in India

1.2 CURRENT APPLICATION OF RCA

The new J-Cube Capital Mall in Singapore (completed in 2011) is an example of the use of recycled coarse aggregate concrete in a structural application. Built on the site of the demolished Jurong Entertainment Centre, the new mall utilized the reclaimed concrete as aggregate in 50% of the new concrete structural elements that comprise the superstructure *(www.ies.org.sg)*. Figure 1.2 illustrates artist renderings of the 200,000 ft^2 mall.

Figure 1.2 J-Cube Capital Mall, Singapore *(www.ies.org.sg)*

A case study from North America was the demolition of the former Stapleton Airport in Denver, Colorado in which 2.1 million kilograms (2100 tonnes) of recycled concrete were utilized from old runway, office and warehouse structures in the construction of the newEnterprise Park at Stapleton (Figure 1.3). In total, 4300 m^3 of recycled concrete incorporating approximately 1400 tonnes of RCA was used in the construction of the tilt-up wall panels, making it the largest application of recycled concrete in a tilt-up application *(Etkin-Johnson, 2012)*.

Figure 1.3 Enterprise Park at Stapleton, Denver, United States *(Etkin-Johnson, 2012)*

1.3 RCA PRODUCTION PROCESS

Once a concrete structure has been demolished, large amount of concrete remain as waste material. Any steel and iron material present is then removed using magnetic torches and electromagnets. The reinforcing steel and the concrete are separated out for further processing. The production of recycled coarse aggregate from the demolished concrete debris involves several steps. Harmful substances present in recycled coarse aggregate could include: glass, plastic, plaster, oil droppings, wood, steel, etc. must be removed and arranged separately. Jaw crushers can provide an acceptable particle size distribution necessary for quality recycled coarse aggregate concrete production. Once the aggregates have been separated from demolished concrete, they must be classified according to their particle size utilizing specified standards such as ASTM C 33. After the recycled coarse aggregate source has been fixed and grading is completed. These studies have mainly involved the testing of high strength RCA concrete *(Ajdukiewicz and Kliszczewicz, 2002)*; the shear strength of RCA concrete *(Gonzalez and Martinez, 2007, Fathifazl 2008)* and the bond strength of RCA concrete with reinforcing steel *(Fathifazl 2008, Choi and Kang, 2008, Xiao and Falkner, 2007)*. However, there are very few case studies of actual structures built utilizing RCA concrete to fully or partially replace NA concrete

Once the aggregates have been passed for use in fresh concrete, the mix design process can begin. Density and water absorption characteristics should be considered in order to ensure adequate workability, initial slump and strength.

1.4 PROPERTIES OF RECYCLED COARSE AGGRGATES

RCA often contains a large amount of attached mortar and cement paste. The volume percentage of old mortar may range from 20% to 30%, depending on the properties of parent concrete and the production process. The attached mortar and cement paste on recycled coarse aggregate are the principal cause of the difference between recycled coarse aggregate (RCA) and natural coarse aggregates. Test results indicated that recycled coarse aggregate has the following technical properties *[Xu and Shi(2006), Xiao, (2008)]*:

1) Low bulk and saturated-surface-dry (SSD) density. The bulk density of recycled coarse aggregate is about 1290–1470 kg/m3.The SSD density of recycled coarse aggregate is about 2310–2620 kg/m^3.
2) High water absorption. The absorptions of recycled coarse aggregate are approximately 8.34% (10 min), 8.82 (30 min) and 9.25% (24 h), which is much larger than that of natural coarse aggregates and might be regarded as the most important characteristic.
3) High porosity. The porosity of RCA is approximately 23.3%, due to high mortar/ cement paste content.

4) High crushing index. Thecrushing index of RCA is approximately 9.2% to 23.1%.

5) High clay content. The clay content of RCA is approximately 4.08%.

In the technical code “Technical code for application of recycled concrete” *(DG/TJ08-2018-2007)*, only recycled coarse aggregate (minimum size over 5 mm) is permitted for producing recycled coarse aggregate concrete. The grading of the recycled coarse aggregate must fall within the allowable limits for natural aggregate in *JGJ 52-2006* “Standard for technical requirements and test method of sand and crushed stone or gravel”. The RCA is classified into two types in terms of their SSD density, water absorption, and brick content. Considering the physical, chemical and physical-mechanical requirements, some limitations are also made for RCA. Table 1.1 lists the requirements for RCA in the technical code *DG/TJ08-2018-2007* and a comparison with those in other international specifications, such as *RILEM (1994), BS8500 (2002) and JIS TRA 0006 (2000)*.

Table 1.1: Requirements for RCA specified in Technical Codes *(Xiao et al. 2012)*

Items	DG/TJ08-2018-2007		RILEM			BS8500	JIS TRA0006
	Type I(Structural use)	Type II	Type I	Type II	Type III		
SSD density (kg/m^3)	≥2400	≥2200	≥1500	≥2000	≥2400	—	—
Absorption (%)	≤7	≤10	≤20	≤10	≤3	—	≤7
Masonry content (%)	≤5	≤10	—	—	—	≤5	—
Crushing value (%)	≤30		—	—	—	—	—
Soundness (mass loss %)	≤18		—	—	—	—	—
Flakiness index (%)	≤15		—	—	—	—	—
Clay content (%)	≤4		—	—	—	—	—
Sulphate content (%)	≤1.0		≤1	≤1	≤1	≤1	
Chlorides content (%)	≤0.25		—	—	—	—	
Organic material (%)	≤0.5		≤1	≤0.5	≤0.5	—	
Fine particle (%)	—		≤3	≤2	≤2	≤5	≤2
Material with SSD<2200 kg/m^3	—			≤10	≤10	—	—
Material with SSD<1800 kg/m^3	—		≤10	≤1	≤1	—	—
Material with SSD<1000 kg/m^3	—		≤1	≤0.5	≤0.5	≤0.5	—
Impurity content (%) (metal, glass, plastics, asphalt and wood)	≤1		≤5	≤1	≤1	≤1	—
Asphalt content (%)	—		—	—	—	≤5	—
Metal content (%)	—		≤1	≤1	≤1	—	—
Sand content (<4 mm) (%)	—		≤5	≤5	≤5	—	—

Table 1.2: Requirements for high quality RCA in *JIS 5021:2005*

Items	Coarse aggregate	Fine aggregate
Oven-dry density, g/cm3	not less than 2.5	not less than 2.5
Water absorption, %	not more than 3.0	not more than 3.0
Abrasion, %	not more than 35	NA
Solid volume percentage for shape determination	% not less than 55	not less than 53
Amount of material passing test sieve 75 μm,	% not more than 1.0	not more than 7.0
Chloride ion content	not more than 0.04	

1.5 POINT TO BE KEPT IN MIND WHILE USING RECYCLED COARSEAGGREGATE

Although, RCA are normally used as direct replacement of coarse aggregate. However, certain points must be kept in mind while using recycled coarse aggregate in concrete

1.5.1 Absorption and Surface Moisture

Aggregates are porous materials and water can be absorbed onto the body of the aggregates. The absorption capacity is generally defined as the total amount of water required to bring the aggregate to a saturated surface dry (SSD) condition. Aggregates may exist in various moisture states: oven dry, air-dry, saturated surface dry, or moist state. Figure 1.4 illustrates the various moisture states of aggregates.

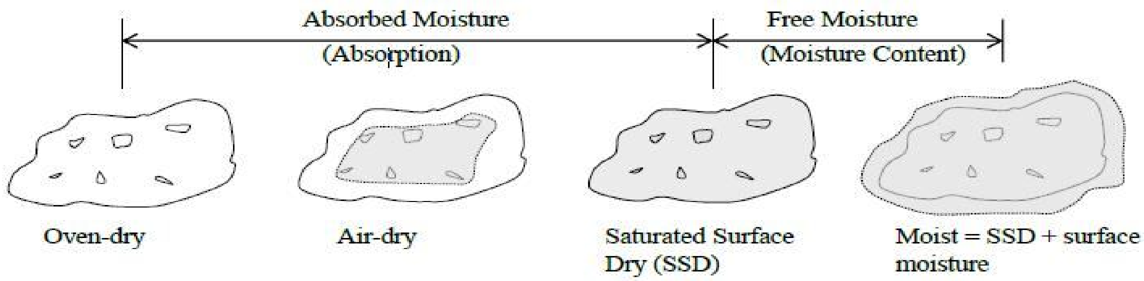

Figure 1.4: Several moisture states of aggregates (Neville, 1995)

A difference must be made between the moisture that is absorbed by the aggregate and the additional water that is observes on the aggregate surface. In concrete mix proportions,it is surface or free moisture that is used to balance the required mixing water. Only free water is available for mixing in concrete and it is this moisture which contributes to the water-cement ratio. It is the size and number of internal pores that are responsible for absorption of water in aggregate and it is seen that recycled coarse aggregates have a higher water requirement than natural aggregates due to the higher water absorption value of adhered mortar. The rate of absorption also plays a significant role in concrete mix proportioning including recycled coarse aggregates. In general, recycled coarse aggregates take longer time to absorb moisture than natural aggregates and, as a result, it may not reach full saturation during the mixing period. Therefore, it has been recommended to pre-soak the recycled coarse aggregates to compensate for the slower absorption rate.

1.5.2 Adhered Mortar Content

After crushing of concrete, the resultant recycled coarse aggregate concrete contains both natural stone and old mortar. This old adhered mortar can account for, about 25 to 60 percent by volume of the aggregate itself. It was noted that the finer the aggregate, the more the adhered mortar content. The residual mortar content can have negative impacts also on such concrete properties as absorption, density, abrasion resistance etc. The amount of residual mortar present on recycled coarse aggregate depends largely on the crushing process by which the aggregates are produced. As the number of crushing of the aggregates increases, the amount of adhered mortar is reduced. It was also observed that use of impact crusher produces higher percentage of recycled coarse aggregate with less amount of residual mortar and it is also suggests that the adhered mortar in recycled coarse aggregate give lower strength then the fresh mortar produced in new concrete. As a result, it concluded that the adhered mortar in recycled coarse aggregates is the weakest point in concrete produced with coarse recycled coarse aggregates.

Several methods have been investigated to determine the percent of residual mortar in recycled coarse aggregate. The most general and commonly used method is taking a sample of oven dried recycled coarse aggregate weighing 100 grams in a plastic container. In this container add 1:3 HCL solution such that the HCL solution surface was 15 mm above the aggregates. And when the level of the HCL falls down after some hours add more HCL in order to maintain the level. After 2 days the constituents of recycled coarse aggregate split up. Transfer the recycled coarse aggregate particles to a new container and add fresh HCL solution as before. Again after 2 days the complete breakdown of recycled coarse aggregate takes place. If it does not, then keep the recycled coarse aggregate immersed for a longer time. After the complete disintegration of recycled coarse aggregate remove the coarse aggregates to a 4.75 mm sieve and wash it with hot water to remove all the HCL. Note down the mass of the oven dried coarse aggregates. The percent of adhered mortar can be calculated based on the following expression:

$$\% \text{ Adhered Mortar} = \frac{\text{Mass of RCA} - \text{Mass of RCA after removal of mortar}}{\text{Mass of RCA}}$$

1.6 ADVANTAGES AND DISADVANTAGES OF RCA CONCRETE

The following are advantages of recycled coarse aggregate

- Recycled coarse aggregate provides sustainability.
- Recycled coarse aggregate reduces the amount of material that would be delivered to a landfill.
- Recycled coarse aggregate reduces the need of virgin aggregates to be created.
- RCA uses 90% less energy in production than the production of portland cement.
- Absorbs large amount of carbon dioxide while being crushed into smaller sizes, reduces the amount of CO_2 in the atmosphere.
- Use of high fineness of fly ash in recycled aggregate concrete yielded greater compressive strength.

The following are disadvantages of RCA

- Recycling plant can cause an increase in noise levels.
- Adhered mortar content have negative impact on absorption and density
- Lack of Specification and Guidelines

1.7 ORGANISATION OF THE THESIS

This thesis has been organized in five chapters as follows:

Chapter- 1. Introduction- It presents various aspects of RCA concrete. This chapter also discuss objective, scope, and the methodology adopted for this investigation.

Chapter- 2. Literature Review- A review of recent literature on bond behaviour of NCA andRCA concrete has been discussed on the basis of which the need of the present investigation has been identified also bond behaviour of reinforced concreteand material characteristic

Chapter- 3. Experimental Programme- Itdescribes the properties of the materials used in thetest specimens, the sizes and the number of specimens, testing methods and the associated instrumentation.

Chapter- 4. Results and Discussions- The analysis of the results, the related discussion and salient observations from the testing have been included in a sequential manner. The results and discussion pertaining to material tests have been presented first and those of the beam tests have been presented later.

Chapter-5.Conclusion- The significant conclusions obtained from experimental investigations of this study have been integrated and presented in a logical sequence and recommendations for further research made.

At the end, references used in this document are presented.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

In this chapter a review of the literature related to bond behaviour of conventionally reinforced concrete member has been carried out. A brief review of the published work on material and structural characteristic of RCA concrete is presented and finally the need of the present investigation is identified.

2.2. EFFECT OF RCA ON FRESH PROPERTIES OF CONCRETE

Some of the required fresh properties of fresh concrete are workability characteristics of concrete, which include slump, loss of slump and bleeding. All these aspects are discussed in the following section.

2.2.1. Initial slump

Neville(1995)pointed out that various mixing conditions such as w/c, water-reducing admixture ratio, and grading and volume of recycled aggregates would control the initial slump of recycled aggregate concrete.

Aggregate type: ***Yang et al.(2008)*** graded the aggregate as per KS14 and found that the initialslump of fresh concrete slightly decreased with the increase of the replacement level of recycled aggregates but was hardly affected by their type.***Poon et al. (2007)***observed that the initial slump slightly increased with the increase of the replacement level of recycled coarse aggregates used in a saturated surface dry state.

Water volume: ***Poon et al.(2004)***studied the moisture condition of the aggregate on initial slump showed that the initial slump of recycled aggregate concrete was significantly affected by the moisture condition of aggregates.

Water in aggregate: ***Lin et al.(2004)***concluded that the initial slump of recycled aggregate concrete was mainly affected by w/c and volume ratio of recycled coarse aggregate rather than the type of recycled aggregates. In addition, particle distribution and shape of aggregates would also have an influence on the initial slump of fresh concrete.

2.2.2. Slump Loss

Yang et al.(2008) found that the slump of fresh concrete nearly linearly decreased withthe lapse of time. He concluded that the type and replacement level of recycled aggregates have a much more significant effect on the workability loss than the initial slump of fresh concrete.

2.2.3 Bleeding

Kimet al.(1993) also concluded that the total amount of bleeding of concretedecreased with the increase of the replacement level of recycled coarse aggregates, as the bleed water could be absorbed by the old cement paste on the surface of recycled aggregates. ***Poon et al.(2007)***showed that the total amount of bleeding of concrete slightly increased with the increase of replacement level of air-dried recycled coarse aggregates. ***Yang et al.(2008)*** observed that the rate of bleeding against the elapsed time decreasedwith increased water absorption of recycled aggregates, also the total amount of bleeding of fresh concrete decreases with the increase of the relative water absorption of aggregates.

2.3 EFFECT OF RCA ON HARDENED PROPERTIES OF CONCRETE

Some of the required hardened properties of concrete are compressive strength, tensile strength, modulus of elasticity and many more. Few of them are discussed in the following sections.

2.3.1. Compressive strength

Xiao etal. (2012) concludes that compressive strengths of recycled coarse aggregate are generally lower than those of conventional concrete. Furthermore, compressive strength values decrease with the increase of RCA amounts.Several reasons could be responsible for the reduction of the compressive strength for RAC, including an increased concrete porosity and a weak aggregate-matrix interface bond.

Butler et al. (2011)however, concluded that recycled coarse aggregate concrete had higher compressive strength values than the natural aggregate concrete. This is likely due to the stronger mortar–aggregate bond between the RCA and the new mortar.

Kim etal. (2012)observed that compressive strength decreased when the coarse aggregate was replaced with the recycled. Additional replacement of the fine aggregate reduced the strength as the recycled fines amount increased. When the fine aggregate replacement was greater than 60% the strength reduction became more significantly. Reason for reduction in compressive strength is (i) remained mortar on the surface of the recycled aggregate, (ii) cracks in the aggregate itself (which could occur during the crushing) and (iii) the original aggregate's strength. From, the observations, it is recommended that the fine aggregate should better be replaced with the recycled less than60% in the consideration of compressive strength.

Poon et al. (2004)studied Influence of moisture states of natural and recycled aggregates on the compressive strength of concrete, and concluded that the concrete mixtures prepared with the incorporation of recycled aggregates, the air dried (AD) aggregate concretes exhibited the highest compressive strength. The surface dried density (SSD) recycled aggregates seemed to impose the largest negative effect on the concrete strength, which might be attributed to ‘‘bleeding’’ of excess water in the pre-wetted aggregates in the fresh concrete.Based on the results of his study, aggregates in the ADstate and contain not more than 50%recycled aggregate should be optimum for normalstrength recycled aggregate concrete production.

Khatib (2005) found that the absorbed water in the recycled aggregate may have helpedwith internal curing by providing a source of water to react with the cement. The relative compressive strength of recycled aggregate concrete decreases with the increase of relative water absorption of aggregate and the relative compressive strength can also be significantly affected by the *w*/*c* and curing condition.

Rahal (2007) when relative water absorption of aggregate is below 1.8%, the compressive strength of recycled aggregate concrete maintains more than 80% of that of the control concrete with natural aggregates, whereas the compressive strength of recycled aggregate concrete having relative water absorption of aggregate above 5.5% drops significantly, by as much as approximately 40% of that of the control concrete with natural aggregates. Insufficient hydration and a weak interface-zone formed between different components of the concrete matrix owing to a large amount of old cement paste on the surface of recycled aggregates, which can be the cause of a poor development of the compressive strength of concrete. Figure 2.1 shows that higher strength can be achieved by reducing the water to cement ratio in recycled concrete aggregate.

Tu et al. (2006) in addition, an inconsistent surface of recycled fine aggregate would produce numerous microcracks between aggregates and cement paste, which would reduce concrete compressive strength.

Chenet al. (2003) study, washed RA is used as coarse aggregate. They found that washed RA comprised higher strength than that of unwashed RA. Greater bond effects were produced when impurities, powder and harmful materials on aggregate surface in RA are washed away. They also identified that at low w/c ratio, the compressive strength ratio of recycled concretes to normal concretes are decreased. Main factor which lead to this result is strength of the paste is increase at low w/c ratio. Based on composite material theory, they revealed that RA will become a weak material and its bearing capacity become smaller which influenced to decrease in strength.

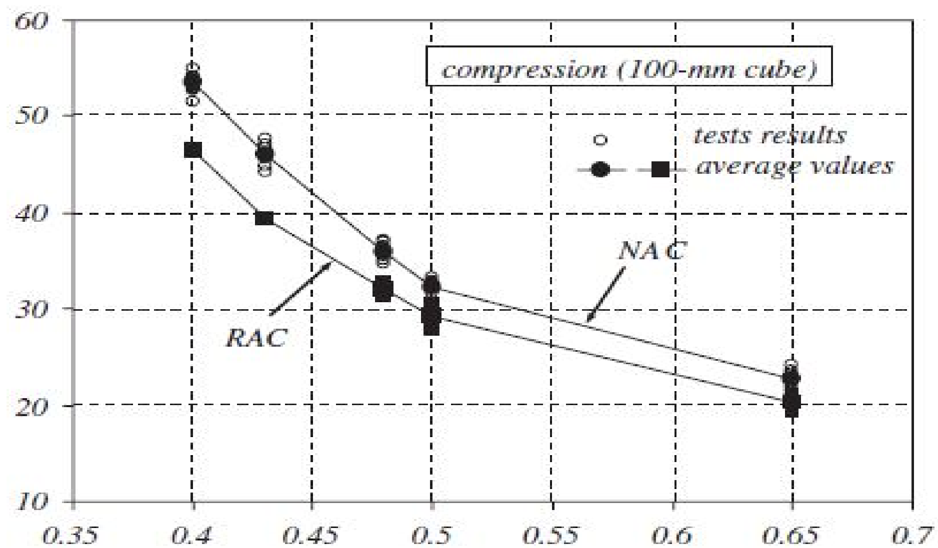

Figure 2.1: 28 days compressive strength versus w/c ratio *(Rahal 2007)*

2.3.2 Splitting tensile strength

Yang et al. (2008) observed that the normalized splitting tensile strength of recycledaggregate concrete decreased with the increase of relative water absorption and it was less than 0.53 for most specimens having relative water absorption larger than approximately 2.25%.***Xiao et al.(2012)***observed that as increase recycled coarse aggregate amount tensile strength decreases, and tensile strength of recycled coarse aggregate concrete is lower as compare to those conventional concrete.***Butler et al. (2011)***found strong relationship between aggregate crushing value (ACV) and splitting tensile strength. As the ACV increase, the splitting tensile strengths become more sensitive.Comparison based on ACV can be made between a particular recycled coarse aggregate source and a natural aggregate source. This comparison could be used as an early indicator of how concrete produced with recycled coarse aggregate will perform, with respect to its splitting tensile strength, compared to concrete produced with natural coarse aggregate.

2.3.3. Modulus of elasticity

The modulus of elasticity of concrete made with Grade I coarse RCA at 100% replacement level was above 4700√f'ck as specified in ACI 318-05. In addition, the elastic modulus of concrete containing Grade II fine RCA was nearly similar to that of concrete with Grade III coarse RCA for the same replacement level. The normalized elastic modulus$E_c/\sqrt{f_{ck}}$ of recycled aggregate concrete decreased with the increase of relative water absorption, indicating that a lower elastic modulus was exhibited by recycled aggregate concrete having relative water absorption above 3.0% than that used in ACI 318-05 for concrete with natural aggregates ***Yang et al.(2008)*** and Yang also pointed out that the impact force during the crushing process of waste concrete would result in poor strength and stiffness of recycled aggregate that would in turn reduce the elastic modulus of recycled aggregate concrete.

2.4 EFFECT OF RCA ON BOND BETWEEN STEEL AND CONCRETE

The bond of reinforcement in concrete is responsible for three main features of structural performance, namely (1) bond is used to anchor the ends of reinforcing bars, (2) bond transfers force from concrete in tension, thereby reducing the strain in the flexural reinforcement and enhancing member stiffness (3) bond is used to maintain the composite action between the reinforcing bar and surrounding concrete. Bond action is also required to ensure sufficient level of ductility in structural members. In design codes, bond is generally assumed as shear stress acting uniformly along the nominal surface area of a reinforcing bar.Practically, the bond stress varies along the length of the rebar and higher at the ends of the rebar. Also, in ribbed rebar, the transfer of load between the reinforcing bar and surrounding concrete is initially through bearing of the ribs.

2.4.1 Mechanisms of Bond Resistance

Followings are various mechanisms due to which the bond between the rebar and concrete exists. The major mechanisms are:-

- ***Chemical adhesion:*** Due to adhesive property in the products of hydration(formed after hardening of concrete).
- ***Frictional resistance:***Due to the surface roughness of the reinforcement barand the

grip applied by the concrete shrinkage.

- ***Mechanical interlock:*** Due to the surface ribs provided in deformed bars. Theresistance due to 'mechanical interlock' is not available in plain reinforcing bar.

Friction starts to play a significant role when ribbed bars are used. Figure 2.2 shows the various bond transfer mechanisms on a reinforcing bar

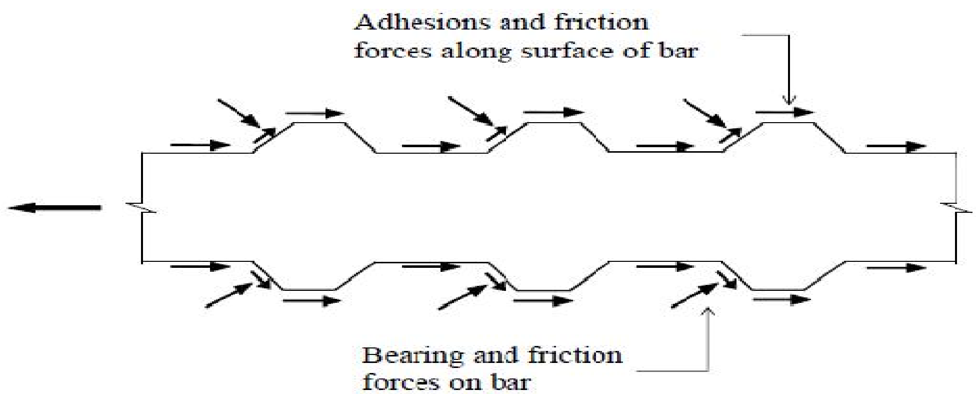

Figure 2.2: Mechanism of bond transfer ***(Wight et al. 2009)***

Bearing and friction forces on ribbed portion of the bar and adhesions and friction forces acting along the surface of bar i.e. compressive bearing force perpendicular to the rib surface increases friction forces parallel to the surface. The forces acting on the rebar surface is balanced by the compressive and shear forces. These compressive and shear forces are then resolute into tensile forces which caused cracks parallel and perpendicular to the reinforcing bar. Generally, splitting cracks may occur if insufficient spacing or cover is provided. If cover, spacing, and transverse reinforcement are inadequate to stop splitting failure then shear failure initiating at the top of the ribs of the bar will occur and a pull-out failure will occur. In general, bond resistance is governed by the following factors:

- The mechanical properties of concrete and its components,
- Concrete cover and bar spacing,
- Transverse reinforcement
- Surface condition of the bar (ribbed, plain, etc.)
- Bar geometry (deformation height, spacing, width, etc.)

2.4.2 Bond between RCA Concrete and Steel Rebars

Bond strength can be measured by various test setups. The most common is Pull out test, in which the load (P) and the slip (s) at the free end of steel rebar anchored in the test specimen were measured in order to determine a load–slip relationship. The monotonically increased load was applied by the testing machine. Other methods used are beam end specimen and splice beam method. The results obtained by various researchers are discussed in the following sections.

(A) Pull-out Method

Xiao et al.(2007) studied the recycled coarse aggregate replacement ratio and the steel rebar style as the main experimental parameters. The main aim of this work is to investigate the bond behaviour between recycled aggregate concrete and steel rebars and to find a bond stress versus slip relationship between recycled aggregate concrete and steel rebar. Thirty six pull-out test specimens were tested in order to investigate the bond behaviour. Steel rebar (i.e. plain and deformed) and recycled coarse aggregate (RCA) replacement percentages (i.e., 0%, 50% and 100%) were the main parameter considered in this paper. The mean values of the bond strengths are compared in Figure 2.3. FromFigure 2.3, it can be concluded that under the equivalent mix proportion (i.e., the mix proportions are the same, except for different recycled coarse aggregate replacement percentages), the bond strength between the recycled aggregate concrete and the plain rebar decreases by 12% and 6% for an recycled coarse aggregate replacement percentage of 50% and 100%, respectively; while the bond strength between the recycled aggregate concrete and the deformed rebar is similar, regardless of the recycled coarse aggregate replacement percentage. Therefore, it is concluded that for the plain rebar, with increase in recycled coarse aggregate replacement ratio, bond strength decreases, whereas for the deformed bar the bond strength between the recycled coarse aggregate and the deformed rebar remains same.

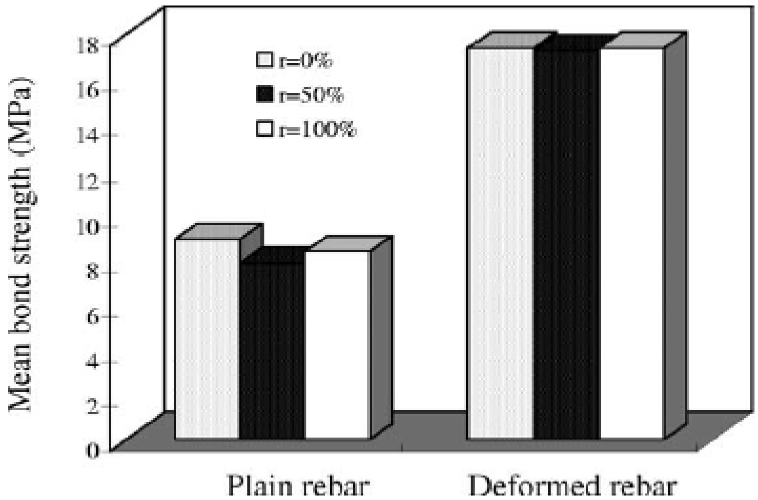

Figure 2.3: Comparison for the mean value of bond strength*(Xiao et al. 2007)*

Choiet al. (2008) investigate the bond performance between recycled coarse aggregate and reinforcing bar. The bond strength against slip relationship between RCA and reinforcing bar is reflected as the main characteristic of reinforced-concrete construction, and the shear strength and shear failure of concrete, which effect bond strength, are also investigated. In addition, this study also checks whether the three known equations that have been most commonly used to obtain the bond strength of concrete from the compressive strength of concrete are also applicable for recycled coarse aggregate. These equations are: the Ogura–Koichi model, CEB–FIP model and ACI 408 model. To investigate the bond behaviour between recycled aggregate concrete (RCA) and rebar, this paper considers recycled aggregates (RAs) (RG of grade I and III and RS of grade II), w/c ratios (40% and 50%), and replacement ratios of RAs (0%, 30%, 50% and 100%). The results were as follows: (a) bond stress–slip shows tendencies like those of normal concrete up to a replacement ratio of 50%; (b) shearing stress–strain is influenced by grade and the replacement ratio of RAs; (c) τ_b is influenced by grade and the replacement ratio of RAs, but at high w/c, τ_b is not influenced by the quality and the replacement ratio of RAs; (d) $\tau_b / \sqrt{f_{ck}}$ is influenced by the w/c ratio; and (e) τ_b between RCA and rebar is overestimated or underestimated by existing equations. As a result, a new equation (with modification of either the value, invariable value or others), or modified development length or lap splice length must be considered. In concrete mix design, the ratio of the amount of RA to that of the total aggregate is termed the RG and RS replacing ratio.

Because the used RAs have high water absorption, they were pre-soaked with additional water before mixing, to make the aggregate state saturated and surface dry in this experiment. Two w/c ratios were used: 0.4 and 0.5. The target slump value for each was 150 mm and 120 mm. The mixtures were divided into six groups, the only difference between the groups being the replacing ratios of RA, which were 0%, 30%, 50% and 100%. The mix proportions for this experiment are given in Table 2.2

Table 2.2: Mix proportions*(Choi et al. (2008)*

Type	w/c: %	Grade		R_{RG}: %	R_{RS}: %	S/A: %	Bulk density: kgf/m^3					
		Coarse	Sand				w	c	NG	NS	RG	RS
N	50	Natural		0					983·7		0	
RG-I 30				30					688·6		301·1	
RG-I 50		I		50					491·9		501·8	
RG-I 100			Natural	100	0				0	726·7	1003·5	0
RG-III 30				30				350	688·6		285·6	
RG-III 50		III		50					491·9		476	
RG-III 100				100					0		952	
RS-II 30					30					508·7		200·8
RS-II 50			II	0	50				983·7	363·4	0	334·6
RS-II 100		Natural			100	42	175			0		669·3
N				0					943·8		0	
RG-I 30				30					660·6		288·8	
RG-I 50		I		50					471·9		481·4	
RG-I 100			Natural	100	0				0	697·2	962·8	0
RG-III 30				30				437·5	660·6		274	
RG-III 50	40	III		50					471·9		456·7	
RG-III 100				100					0		913·3	
RS-II 30					30					488		192·6
RS-II 50		Natural	II	0	50				943·8	348·6	0	321
RS-II 100					100					0		642·1

The mean pull-out bond strength as a function of both RA ratios and w/c ratios is shown in Fig. 2.4. In w/c ratio 0.5, the bond strength decreased with the increasing RA ratio and the decrease grade/class of RA. Thebond strengths of all specimens that used RA were, however, higher than those of normal concrete (N). The bond strength increased as the w/c ratio decreased. This may be because the bond strength between RAC and the rebar depends on the concrete type and properties, mechanical anchorage and friction resistance. That is, concrete type and properties are different according to the RA used, and this difference changed the mechanical anchorage and friction resistance between the two materials. The bond strength can therefore be considered to be strongly influenced by RA ratio, among numerous other factors. The average bond strength of RS-II concrete was lower than that of RG-III concrete.

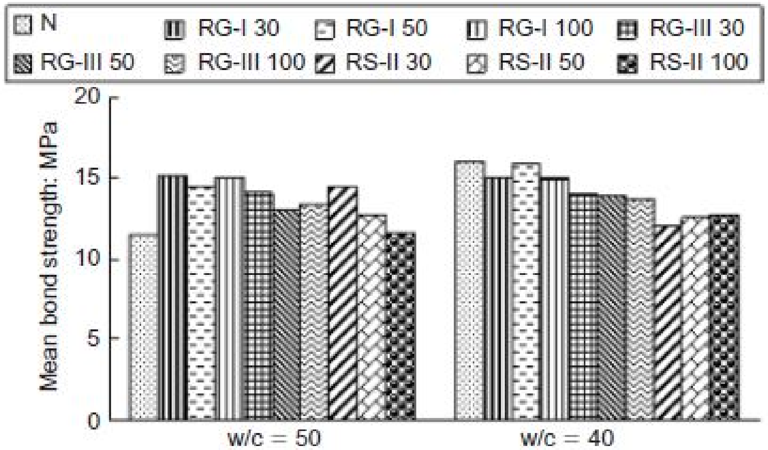

Figure 2.4: Mean pull-out bond strength with the replacement ratio of RA$_s$and w/c ratio. ***(Choi et al. (2008)***

The type of RA (RG or RS) has a larger negative effect on the bond strength of RAC than the quality of the RA Interestingly, concretes using relatively goodqualityRS still had a poorer performance than concretesthat used RG in the bond.

In w/c ratio 0.4, the bond strength between the RACand the rebar decreased with an increasing RA ratioand a decreasing RA grade/class—a trend similar tothat of the w/c ratio 0.5. In contrast, however, with the w/c ratio of 0.5, the bond strengths of all specimensthat used RA were lower than that of normal concrete.When the RA ratio was 100% and the w/c ratios werethe same, the bond strength—as a function of the RAratio—increased by 22.7% (5RG-I 100), 13.6% (5RGIII100) and 0.1% (5RS-II 100) for a w/c ratio 0.5, anddecreased by 7.1% (4RG-I 100), 16.3% (4RG-II 100)and 26.1% (4RS-II 100) for a w/c ratio of 0.4 morethan that of normal concrete (5N and 4N). These results show that the bond strength of RAC was hardly influencedby the w/c ratio but was greatly influenced bythe replacement ratio and the grade of the RA.

(B) Beam-end specimens

Butler et al. (2011) investigateconcrete bond strength by replacing natural coarse aggregate with recycled coarse aggregate (RCA). For the investigation two sources of RCA were used along with one natural aggregate source. All the aggregate properties were tested for all aggregate sources. Two different types of concrete mix proportions were developed in which 100% of the natural aggregate was replaced with RCA. In the first one the same water–cement ratio was maintained and in the second type the mix proportion was designed to achieve the same compressive strengths. Beam-end specimens were casted. The mix proportions obtained are shown in table 2.3 & 2.4

Table 2.3: Control concrete mixture proportions and test results.*Butler et al. (2011)*

Material	NAC-30	NAC-50
Water (kg/m^3)*	160	180
Cement (kg/m^3)	267	474
Coarse aggregate (kg/m^3)	1106	1106
Fine aggregate	861	633
Water–cement ratio	0.60	0.38
Slump (mm)	90	90
Compressive strength (MPa)	34.4	54.7

* Water content values reported do not include adjustments for aggregate water absorption.

Table 2.4: strength based concrete mix proportion and test results.*Butler et al. (2011)*

Material	RAC1-30	RAC1-50	RAC2-30	RAC2-50
Water (kg/m^3)	175	190	165	190
Cement (kg/m^3)	243	404	262	500
Coarse aggregate (kg/m^3)	970	970	919	919
Fine aggregate (kg/m^3)	848	672	889	621
Water–cement ratio	0.72	0.47	0.63	0.38
Slump (mm)	80	85	90	85
Compressive strength (MPa)	35.3	53.5	31.5	50.6

*Water content values reported do not include adjustments for aggregate water absorption.

The strength-based mixtures were developed for two reasons: (1) to determine whether RCA mix proportions could be developed to obtain similar compressive strength and workability to that of natural aggregate concrete and (2) to determine the effect that natural aggregate replacement with RCA has on bond strength.Figure 2.5 shows the test apparatus used in this investigation

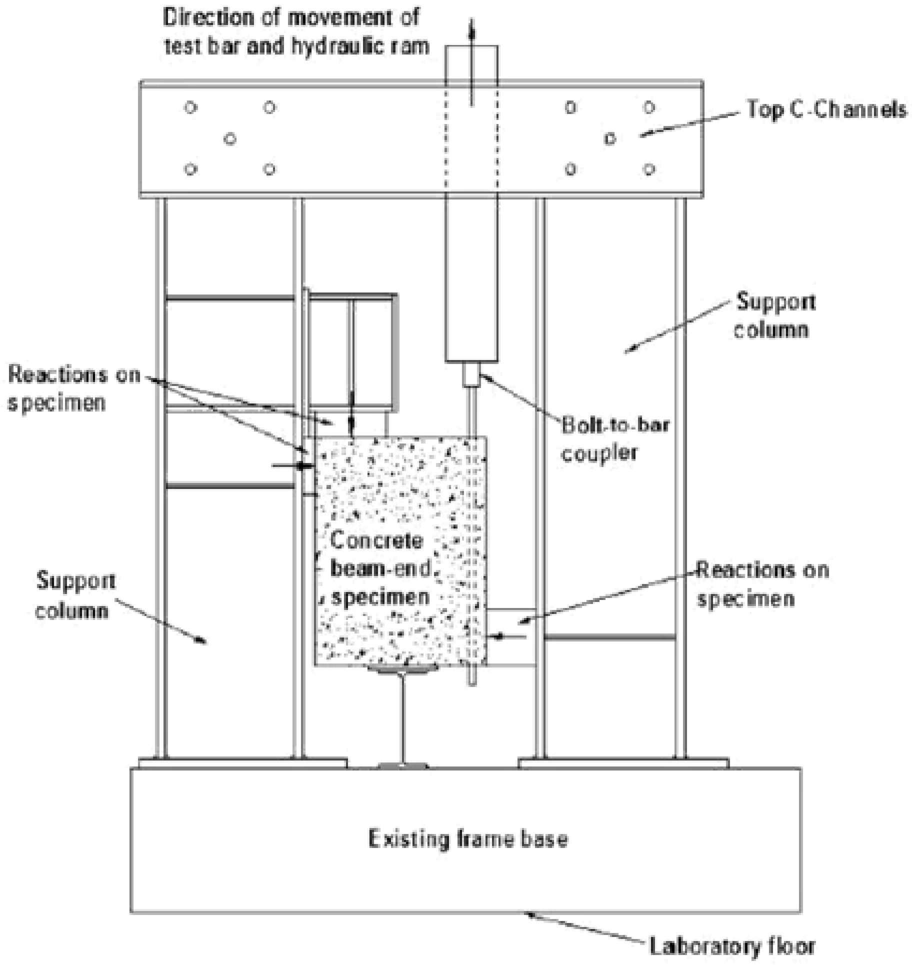

Figure 2.5: Beam-end test frame set-up *(Butler et al., 2011)*

Beam-end specimens were tested to investigate the relative bond strength of RCA and natural aggregate concrete.Average bond stress values,for the 125 mm and 375 mm bonded lengths are summarized in Fig. 2.6 (a) and (b), respectively.The natural aggregate concrete beam-end specimens with bonded lengths of 125 mm had average bond strengths that were 11.4 to 19.0% higher than the RCA-1 concrete specimens and 13.2 to 21.3% higher than the RCA-2 specimens. It was concluded that, natural aggregate concrete specimens had 9 to 19% higher bond strength value than the equivalent RCA specimen.

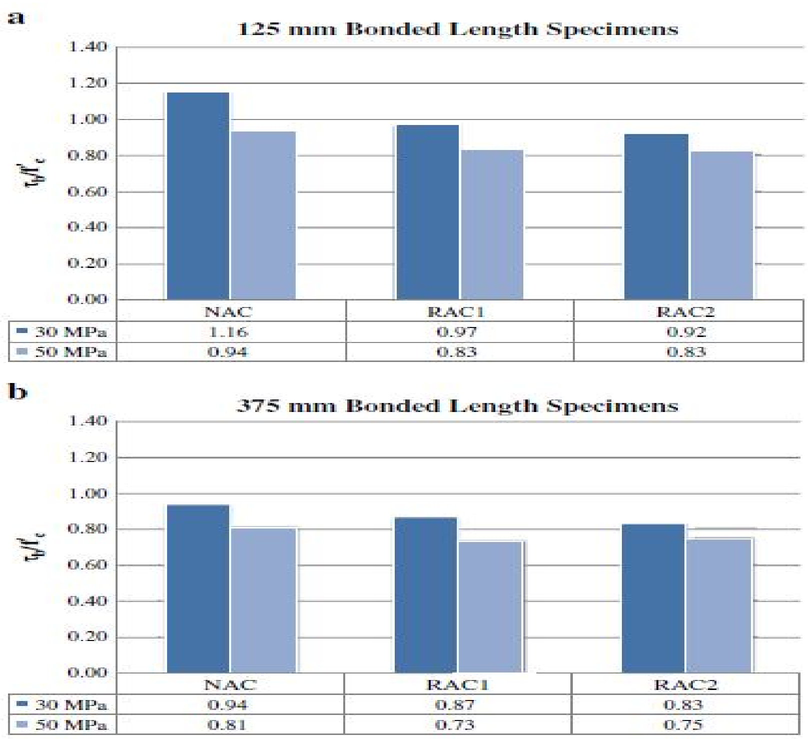

Figure 2.6 (a) and (b): Average bond stress data for NAC, RAC1 and RAC2 (a) 125 mm bonded length specimens. (b) 375 mm bonded length specimens.
(Butler et al., 2011)

2.5 NEED OF THE PRESENT INVESTIGATION

A review of the literature shows that although bond behaviour of natural aggregate concrete has been extensively investigated in the past relatively few studies have been reported on bond behaviour of recycled coarse aggregate concrete. Moreover, a majority of such studies have used the pull-out test which is a relatively inaccurate method for assessing bond behaviour.

2.6 CLOSING REMARKS

A review of recent literature on bond behaviour of natural coarse aggregate and recycled coarse aggregate concrete has been presented on the basis of which the need of the present investigation has been identified.

CHAPTER 3
EXPERIMENTAL PROGRAMME

3.1 INTRODUCTION

The details of experiment programme in terms of material properties, test set-up for measuring different parametersare the testing procedurediscussed in this chapter.

3.2 MATERIAL PROPERTIES

Cement, fine aggregates, coarse aggregates, recycled coarse aggregate, super-plasticizer and water is used for present investigation. The propertiesof these materials are discussed in the following sections.

3.2.1 Cement

Cement is a fine, grey powder. It is mixed with water and materials such as sand, gravel, and crushed stone to make concrete. The cement and water form a paste that binds the other materials together as the concrete hardens. The ordinary cement contains two basic ingredients namely argillaceous and calcareous. In argillaceous materials, clay predominates and in calcareous materials calcium carbonate predominates. Ordinary Portland cement of grade – 43 (Ultra tech cement) conforming to Indian standard IS: 8112-1989 has been used in the present study. The results of the various tests on cement properties are given in Table 3.1.

Table 3.1: Physical properties of Portland cement

Sr. No.	Characteristics	Values obtained	Standard values
1.	Normal Consistency	29.5%	-
2.	Initial setting time	1 hours 55 min	Not to be less than 30 minutes
3.	Final Setting time	3 hours 40 min	Not to be greater than 600 minutes
4.	Fineness	2.5%	<10%
5.	Specific gravity	3.38	-

3.2.2 Fine Aggregates

The material which passes through 4.75 mm sieve is termed as fine aggregate. Usually natural sand is used as a fine aggregate at places where natural sand is not available crushed stone is used as a fine aggregate. The sand used for the experimental works is locally procured and conformed to grading zone III. The sieve analysis of fine aggregates is shown in Table 3.2. The physical properties are provided in Table 3.3

Table 3.2: Sieve Analysis of fine aggregates

S. No.	Sieve No.	Weight Retained (gms)	Percentage Retained%	Percentage Passing %	Cumulative % Retained
1.	4.75 mm	95	9.5	90.5	9.5
2.	2.36 mm	42.5	4.25	86.25	13.75
3.	1.18 mm	110.5	11.05	75.2	24.8
4.	600 mm	128.5	12.85	62.35	37.65
5.	300 mm	308.0	30.8	31.55	68.45
6.	150 mm	281.0	28.1	3.45	96.55
7.	Pan	34.5	3.45	----	----
				∑F=	250.5

Fineness Modulus of fine aggregate = ∑F/100 = 250.5/100=2.50

Table 3.3: Physical properties of fine aggregate

S. No.	Characteristics	Value
1.	Type	Natural Sand
2.	Specific Gravity	2.65
3.	Fineness Modulus	2.505
4.	Grading Zone	III

3.2.3 Natural Aggregate

The broken stone is generally used as a coarse aggregate. The nature of work decides the maximum size of the coarse aggregate. Locally available coarse aggregate having the maximum size of 20 mm was used in the present work. The properties of natural aggregate are presented Table 3.4

3.2.4 Recycled Coarse Aggregate

Large amount of tested concrete specimens e.g. cubes, cylinders, beams etc. were lying in the concrete laboratory ofThapar University. These specimens were used as a source of RCA concrete. To make RCA, the specimens without reinforcement were manually broken down into small pieces and then crushed using jaw crusher as shown in Fig. 3.1. The crushed pieces of concrete were then separated into two fractions depending on their size. The larger fraction, passing through 20 mm sieve but retained on 10 mm sieve was designated RCA20 – 10 mm, while the smaller fraction passing through 10 mm sieve but retained on 4.75 mm was designated RCA10 - 4.75. The fraction passing through 4.75 mm sieve was discarded. While making RCA concrete, the two different sizes of RCA were mixed in a suitable proportion so that the gradation curve of the combined RCA concrete was similar to that of the natural coarse aggregate.

Figure 3.1: (a) Waste concrete used for producing RCA (b) RCA obtained from the jawcrusher

3.2.4.1. Gradation of Coarse recycled concrete aggregate and Natural aggregate

While making recycled coarse aggregate concrete, the size fractions of recycled coarse aggregate 20 - 10 and RCA 10 - 4.75 were mixed by the method of equivalent mix proportion so that the gradation curve of the combined recycled coarse aggregate was similar to that of the natural coarse aggregate. The final mix ratio for recycled coarse aggregate was achieved as 70% of RCA 20-10 mm and 30% of RCA 10-4.75 mm. The mix proportion of different size fraction of RCA was decided by hit and trial method. Table 3.4 and 3.5 shows the sieve analysis results of the natural coarse aggregates and recycled coarse aggregate respectively. It may be seen in Table 3.6 that the recycled coarse aggregate satisfies the IS 383:2007 specified gradation criteria for 20mm sized aggregates.

The recycled coarse aggregate gradation curves in Fig. 3.2 are seen to have a close resemblance to the NA gradation curves and hence the size distribution of the recycled coarse aggregate particles is acceptable.The physical properties of coarse aggregates (both natural and recycled) used are provided in Table 3.6.

Table 3.4: Gradation of natural coarse aggregate

Sieve size (mm)	**% passing Required [IS383:1970]**	**Weight retained (kg)**	**Cumulative % weight Retained**	**%passing forNA**
20	100	0	0	100
12.5	90-100	1.040	12.4	87.6
10	40-85	3.50	47.4	52.6
4.75	0-10	4.77	95.1	4.9

Table 3.5: Gradation of recycled coarse aggregate

Sieve size (mm)	**% passing Required [IS383:1970]**	**Weight retained (kg)**	**Cumulative % weight Retained**	**%passing for RCA**
20	100	0	0	100
12.5	90-100	1.040	12.4	85.7
10	40-85	3.50	47.4	58.3
4.75	0-10	4.77	95.1	3.5

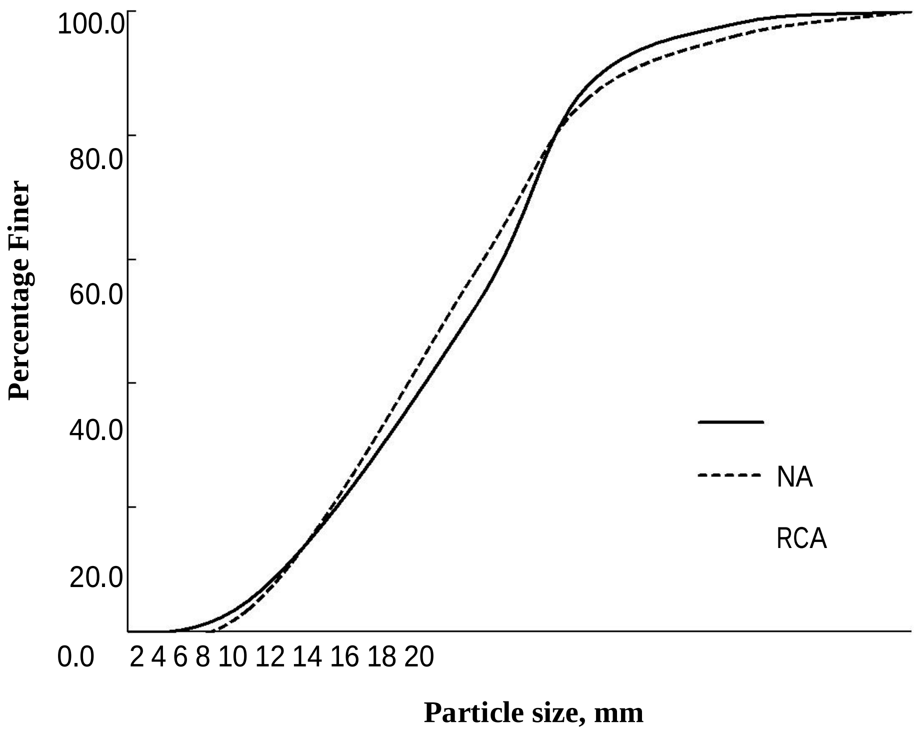

Figure 3.2: Gradation curve of coarse aggregate

Table 3.6: Physical properties of the recycled and natural course aggregate

Properties	**Natural Aggregate**	**Recycled Coarse Aggregate**
Specific gravity	2.34	2.6
Water absorption (%)	1.6	2.4
Fineness modulus (%)	6.7	7.1

3.2.5 Reinforcing steel

High strength deformed steel bar with a nominal diameter of 16 mm of tensile strength 533.412 MPa, is used as main longitudinal reinforcement in all pull out test specimens. Along with the main bar, the cube is reinforced with a helix of 6 mm diameter plain mild steel reinforcing bar conforming to Grade I of IS: 432 (Part I)-1982 at pitch 25 mm pitch, such that the outer diameter of the helix is equal to size of the cube.

3.2.6 Water

Water is an important ingredient of concrete as it actively participates in the chemical reaction with cement. Since it helps to form the strength giving cement gel, the quantity and quality of water is required to be looked into very carefully. Potable water is generally considered satisfactory. In the present investigation, tap water is used for both mixing and curing purposes.

3.2.7 Superplasticizer

SikaViscoCrete -SC 001, the superplasticizer supplied by Sika India Pvt. Limited is used in our investigations. It is a third generation highly effective superplasticizer for concrete and mortar. It meets the requirements for superplasticizer according to EN934 -2, SIA 262, ASTM C 494-99/99a Type F and 9103-1999 (amended 2003). The dosage of the superplasticizer is fixed based on the requirements for workability. The technical data related to the superplasticizer used is provided in Table 3.7. This data is supplied by the manufacturers.

Table 3.7: Technical data of Super plasticizer

S. No.	Characteristic	Value
1.	Color	Dark brown liquid
2.	Specific gravity	1.17
3.	Air Entrainment	Maximum 1%
4.	pH	7 to 8

3.3 MIX DESIGN

Concrete mix has been designed using the IS code 10262:2009. All the mixes are designed by keeping the water content constant. The desired workability of the mix is kept at 50-60 mm slump. To achieve the required workability of concrete mix, water reducing admixture i.e. superplasticizer, namely sikavisco crete-SC001 is added to the matrix at a desired dosage rate. Concrete mixture proportion and superplasticizer dosage rate is presented in Table 3.8. The mix proportion of corresponding mixes for each water-cement ratio is prepared by replacing natural aggregate by recycled coarse aggregate. In this, mixture proportions for the natural coarse aggregate and the recycled coarse aggregate concretes were nominally kept the same, except for replacement of NCA with recycled coarse aggregate, depending upon the desired recycled coarse aggregate replacement percentage. The recycled coarse aggregate replacement percentage is defined as the weight ratio of recycled coarse aggregate to the total coarse aggregates in the concrete mixture and depending upon the selected replacement percentage, direct substitution of NCA with an equal weight of recycled coarse aggregate particles is carried out. The following four weight combinations of NCA and recycled coarse aggregate are adopted: 100 % NCA (control mixture), 60 % NCA + 30 % recycled coarse aggregate, 30 % NCA +60 % RCA, 10 % NCA +90 % RCA. The concrete mixture proportions and the corresponding mix designations arepresented in Table 3.9.In concrete batching, first the natural coarse aggregates and RCA are added in the mixer, subsequently, fine aggregates and cement are added to the mixer the ingredients are dry mixed in the mixer for 2 minutes. Then half of water is added and again mixed for 1 minute. After this, the rest of the water along with the quantity of required superplasticizer is added and mixed for another 2 minutes. The mixture is now ready to be poured in the moulds.

Table 3.8 Mix proportion for controlled sample

w/c ratio	Cement (kg/m^3)	Fine aggregate (kg/m^3)	Natural aggregate (kg/m^3)	Water (kg/m^3)	Superplasticizer (% by weight of cement)
0.42	486	640	1256	206	1.4%
0.45	453	651	1274	206	1.2%
0.48	426	657	1291	206	1.0%
0.51	400	664	1303	206	0.5%
0.55	370	672	1312	206	0%

Table 3.9 Mix proportion for mixes different rep0lacemetns of NA and RCA

Designation	w/c Ratio	Replacement (%)	Cement (kg/m^3)	Fine aggregate (kg/m^3)	Natural aggregate (kg/m^3)	Recycled aggregate (kg/m^3)	Water (kg/m^3)
A1–0	0.42	0	486	640	1256	-	206
A1–30		30	486	640	879	376	206
A1–60		60	486	640	376	879	206
A1–90		90	486	640	124	1131	206
A2–0	0.45	0	453	651	1274	-	206
A2–30		30	453	651	891	382	206
A2–60		60	453	651	382	891	206
A2–90		90	453	651	131	1152	206
A3–0	0.48	0	426	657	1291	-	206
A3–30		30	426	657	903	388	206
A3–60		60	426	657	388	903	206
A3–90		90	426	657	129	1162	206
A4–0	0.51	0	400	664	1303	-	206
A4–30		30	400	663	912	391	206
A4–60		60	400	663	391	912	206
A4–90		90	400	663	130	1173	206
A5–0	0.55	0	370	672	1312	-	206
A5–30		30	370	672	918	394	206
A5–60		60	370	672	394	891	206
A5–90		90	370	672	131	1179	206

3.4. CASTING OF SPECIMENS

In this section casting procedure for compressive strength test and pull out strength test are discussed

3.4.1 Casting for CompressiveStrength test

150mm cube is used to study the compressive strength of various mixes. The cubes are filled with fresh concrete using vibrating table. Immediately after casting cubes, the specimens are covered with gunny bags to prevent water evaporation. Three cubes are casted for each parameter. The compressive strength test is carried out for 7 days and 28 days. Therefore, six identical specimens are casted for each concrete mix. The cubes after casting are shown in Figure 3.3.

Figure 3.3: Casting of cubes

3.4.2 Casting forPull out strength test

Pullout specimens are widely used for investigation of bond behaviour between rebar and concrete because of their ease of fabrication and the simplicity of the test. Pullout tests provide a simple means of comparing normalized bond behaviour. In the present investigation,cube ofsize150mmisused for carrying out the pull out strength test. The specimen is prepared as per the codal guidelines from IS: 2770 (Part I) – 1967 (Methods of testing bond in reinforced concrete). In this, one rebar of 16 mm diameter is used as concentric reinforcement that will be pulled for finding pull out strength. The pulls out specimens are cast in a vertical position in the laboratory using steel moulds. The embedded length is kept five times the rebar diameter and was so selected to avoid yielding of the steel bar under pullout load. Contact between the concrete and the rebar along the debonded length was broken using a coaxially placed soft plastic tube and the annular space between the rebar and the plastic tube was filled with clay. Along with this, a helix reinforcement (as specified by IS: 2770 (Part I) – 1967) of 6 mm diameter conforming to grade I of IS: 432 (Part I) – 1966 at pitch of 25 mm such that the outer diameter of the helix is equal to the size of the cube.

In present test for casting of the cubes, steel moulds are taken and helix is placed in the moulds leaving a small cover at the bottom and sides. Then the 16mm dia. bar is placed exactly in the centre. Then in the mould, the concrete mixed is poured and compacted using vibrating table.

To prevent excessiveevaporation from the fresh concrete, the pulloutspecimens are covered with a plastic sheet after casting and demoulded after 24 h following which they are moist cured in the laboratory for a nominal period of 28 days from the day of casting by keeping them wet by gunny bags. The water is sprinkle on gunny bags, twice a day.

To ensure repeatability of results, two nominally identical companion specimens are cast for each mix under investigation. The typical sample specimens are shown in Figure 3.4.

Figure 3.4: Pull out test concrete specimens

3.5 TESTING OF SPECIMENS

In this section test setup for both the tests (compressive strength test and pull out strength test) are discussed.

3.5.1 Test setup for Compressive Strength test

As shown in Figure 3.5, three identical specimens are crushed at 7days and three identical specimens are crushed at 28 days.The compressive strength is calculated by dividing the failure load by average cross sectional area.

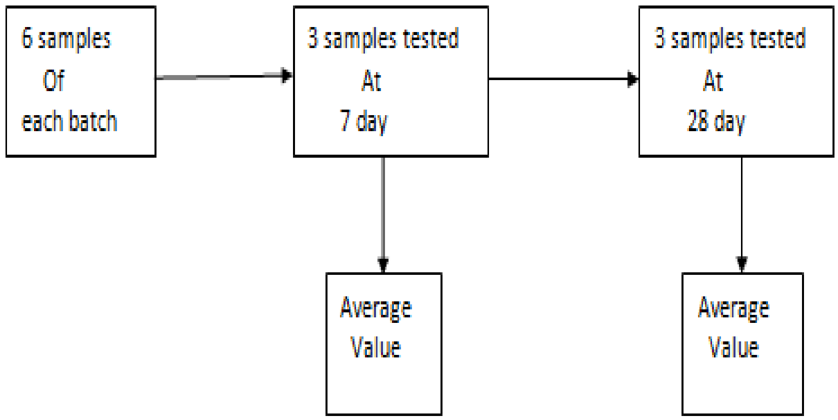

Figure 3.5: Compressive strength evaluation chart of concrete cube specimens

The compressive strength testing machine of capacity 3000 KN is used for determining the maximum compressive loads carried by concrete cubes. The compressive strength test machine which used in all tests is shown in Figure 3.6. At the test age the specimens are taken out of the curing tank and kept outside for 10 minutes. Then one specimen is placed on the steel platen of the machine such that the specimen is tested perpendicular to the casting position. Then the test is carried out at the loading rate of 5 KN/s specified IS: 516 – 1959.

Figure 3.6: Compressive strength test machine

3.5.2 Test setup for Pull out Strength

Pull out strength test are carried out on universal testing machine of capacity 1000 KN shown in Figure 3.7

Figure 3.7: Pull out test machine

The test setup for pull out test is shown in Figure 3.8. A special arrangement of 40 mm thick steel plate is made to carry out the test shown in Figure 3.9. The plates are connected by four nut-bolts of 25 mm diameter. Lower plate is welded with rod having diameter 25mm. And opening at the top plate just allow the deformed steel bar to pass.

Figure 3.8: Test setup for pull out strength test

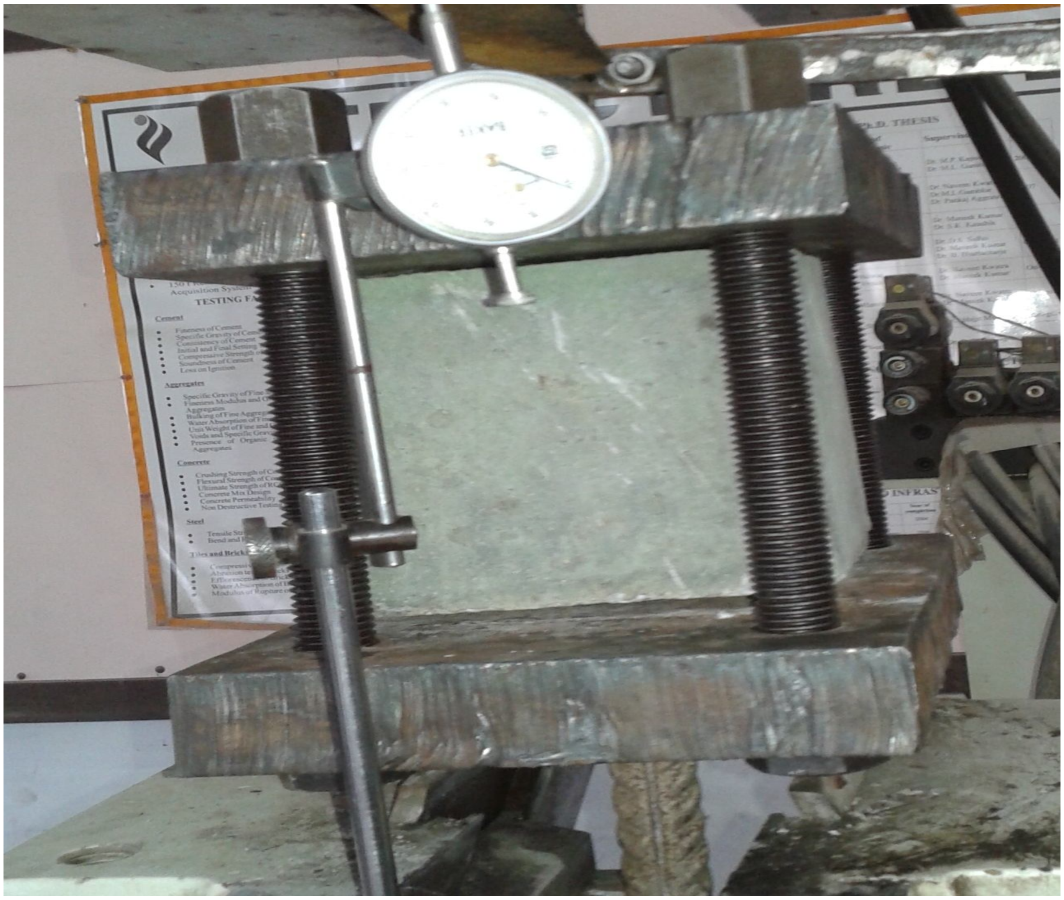

Figure 3.9: Special arrangement of steel plates containing cube

To carry out test, the rod of 25 mm is welded to lower plate of the setup is fixed in the lower jaw of the machine. The specimen is kept in between the two plates and is fixed by tightening the nut-bolts. The 16mm diameter rebar (embedded in the specimen) is passed through the hole in the upper plate and is fixed to the upper jaw of the universal testing machine. The rebar is pulled out at the rate of 2.25 kg/min for all test specimens.

Figure 3.10 shows the dimensions of pull out test specimens, the location and the length of embedded deformed steel bar in concrete specimens. The bond strength is calculated by dividing the pull out force by the surface area of the embedded length of steel bars as follows:

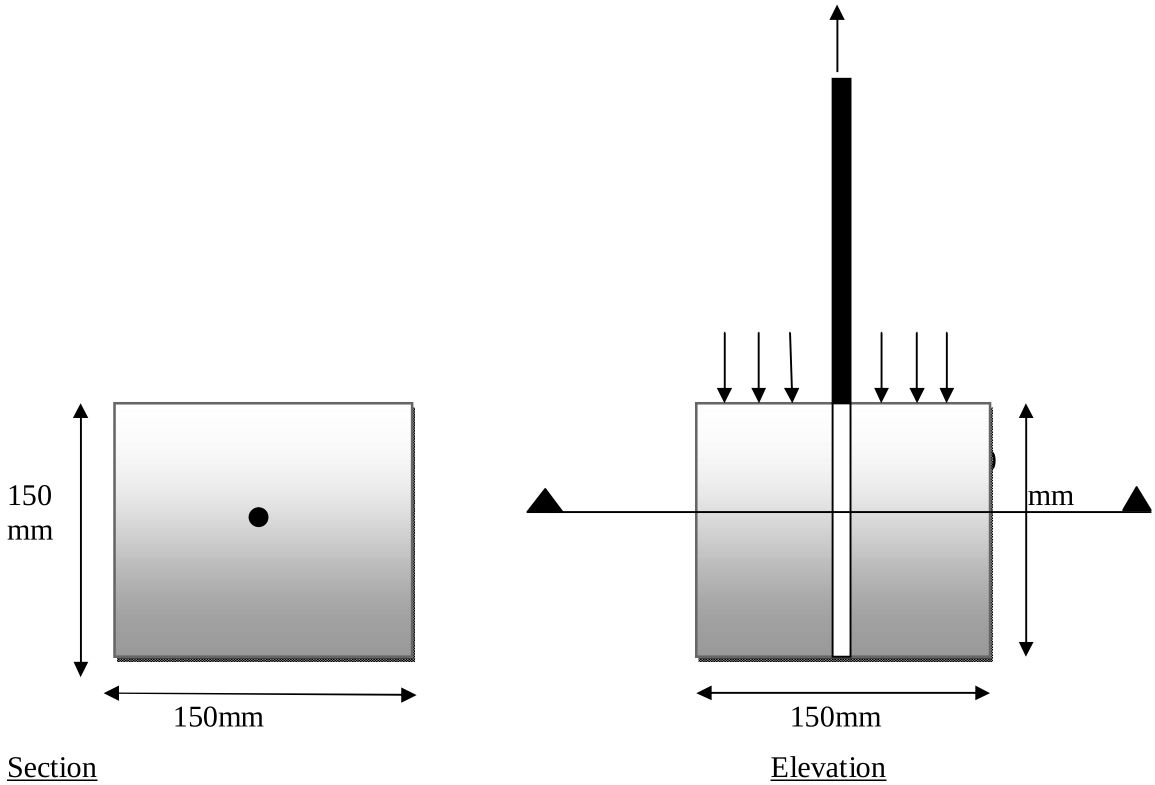

Figure 3.10: The dimensions of pull out test specimens, the location and the length ofembedded deformed steel bar in concrete specimens

$$Bond\ strength = \frac{P}{\pi DL}$$

Where, P: pull out load, (KN)

D=Diameter of steel rod, it is kept as 16mm for experimental programme.

L=embedded length, the value is taken as 80 mm for experimental programme.

The pull out strength test is carried out at the age of 28 days. Two samples are tested for each mix at the specified age. The average value of the two samples was taken as the bond strength of the batch. The layout diagram of the test is shown in Figure 3.11

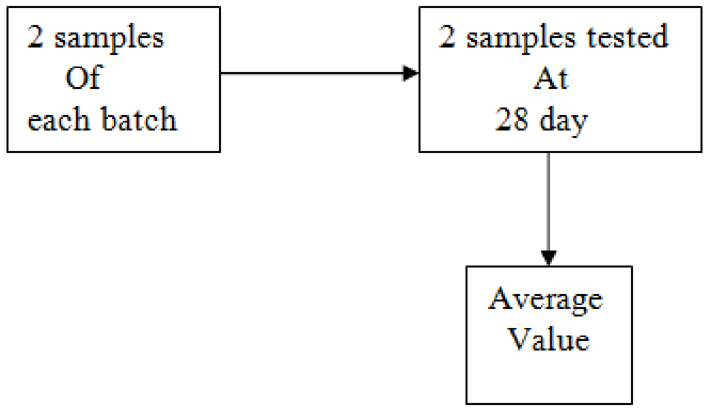

Figure 3.11: Pull out evaluation chart for concrete cube samples

After completion of test, sample was removed from thetest setup, physical verification of crack and type of slip is observed as shown in Fig.3.12. It is observed thatspecimen failed by pullout rather than by splitting ofconcrete.

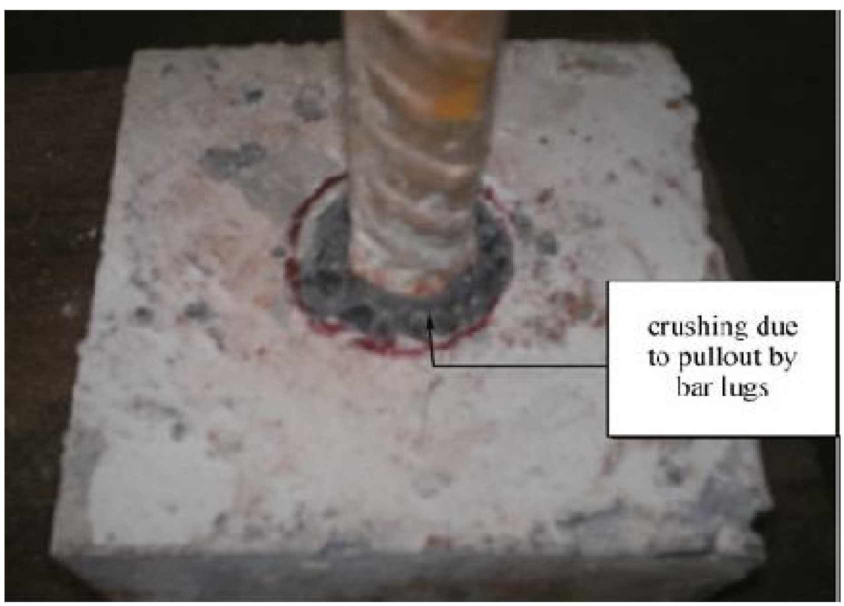

Figure 3.12: Crushing due to pullout bar lugs after pullout test

3.6 CLOSING REMARKS

The experimental programme described in this chapter includes the significant material properties and specifications of the ingredients of concrete; reinforcement steel etc., the testing procedure. The specimen details and the test set-up have been discussed.

CHAPTER 4
RESULTS AND DISCUSSIONS

4.1 INTRODUCTION

In the first part of this chapter, the effect of replacement ratio of recycled coarse aggregate on compressive of concrete is discussed. The effect is studied at a range of w/c ratios.
The second part consists of discussion on the effect of recycled coarse aggregate on the bond strength of concrete.

4.2. COMPRESSIVE STRENGTH

Three cubes (150mm) from each batch of concrete mix are casted and cured for 7 and 28 days in order to determine compressive strength of RCA concrete. All specimens are cast in a single mix and direct weight to weight replacement of natural coarse aggregate is carried out with recycled coarse aggregate at a replacement ratio of 0, 30, 60, and 90 %. The mixes are casted at water-cement ratio of 0.42, 0.45, 0.48, 0.51 and 0.55. This corresponds to range of strength varying from low strength concrete to moderate strength concrete. Table 4.1 shows the value of compressive strength of cube tested at 7 and 28 days. The data is further represented in the form of bar graphs in Figure4.1 - 4.5, for water- cement ratio of 0.42, 0.45, 0.48, 0.51 and 0.55 respectively. The results obtained are discussed in the following sections:

4.2.1 Effect of recycled coarse aggregate on compressive strength

As can be seen from Figure 4.1 - 4.5, for all water-cement ratios, the 28 days compressive strength increases as the percentage of replacement increases. Maximum compressive strength is achieved at 90% replacement at all water-cement studied. However the same trend is not seen at 7 days strength, where the strength decreases initially and then increases. The final compressive strength is lesser than the compressive of control mixes. It may be because at 7 days, the hydration is not complete.

Table 4.1: Cube compressive strength 7 and 28-day

Specimen ID	Water-cement ratio	Replacement (%)	Compressive strength	
			7 days (MPa)	28 days (MPa)
A1-0	0.42	0	40.75	49.07
A1-30		30	35.80	43.65
A1-60		60	39.7	50.06
A1-90		90	40.7	52.31
A2-0	0.45	0	36.37	41.68
A2-30		30	29.13	41.28
A2-60		60	33.75	45.64
A2-90		90	35.50	50.66
A3-0	0.48	0	32.20	36.04
A3-30		30	26.04	39.65
A3-60		60	28.08	43.15
A3-90		90	31.56	44.73
A4-0	0.51	0	28.67	32.48
A4-30		30	19.07	33.30
A4-60		60	25.60	38.78
A4-90		90	28.03	40.97
A5-0	0.55	0	23.02	24.89
A5-30		30	16.40	30.03
A5-60		60	18.90	35.86
A5-90		90	19.87	37.68

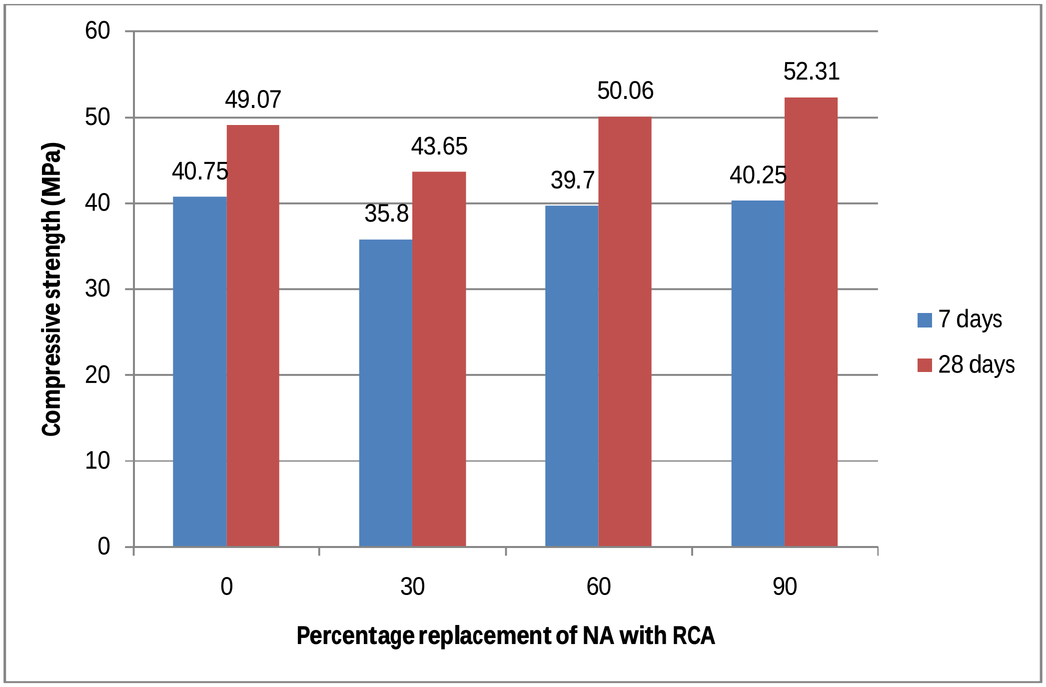

Figure 4.1: 7 and 28 days compressive strength for w/c ratio 0.42

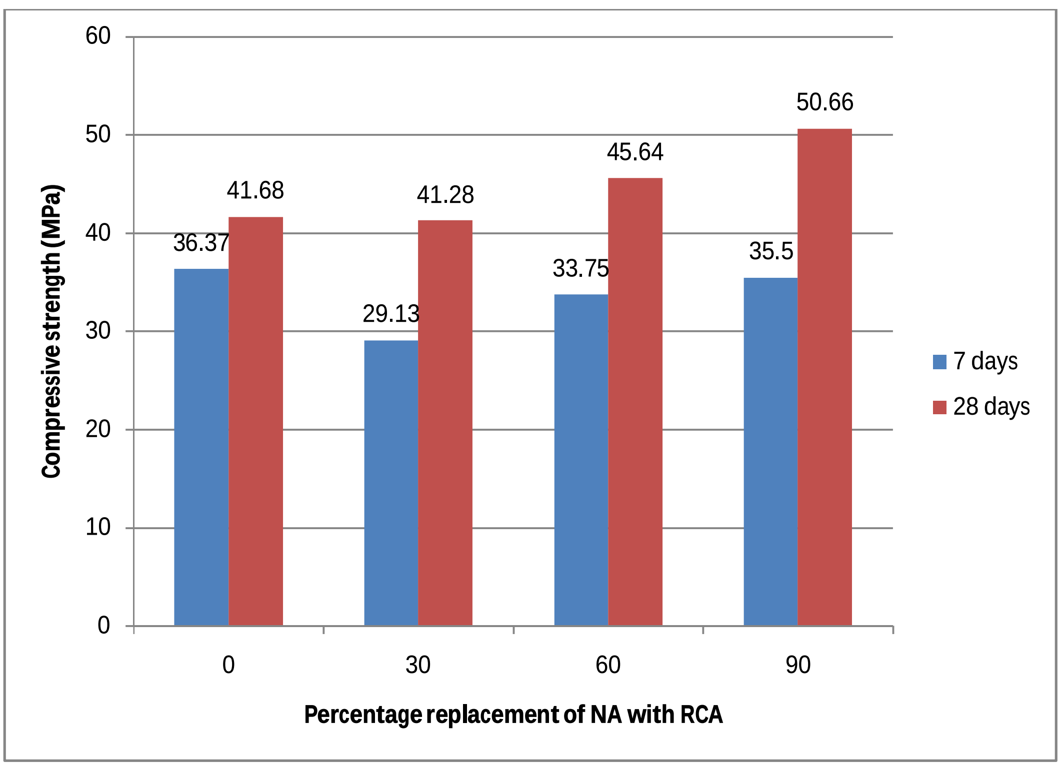

Figure: 4.2: 7 and 28 days compressive strength for w/c ratio 0.45

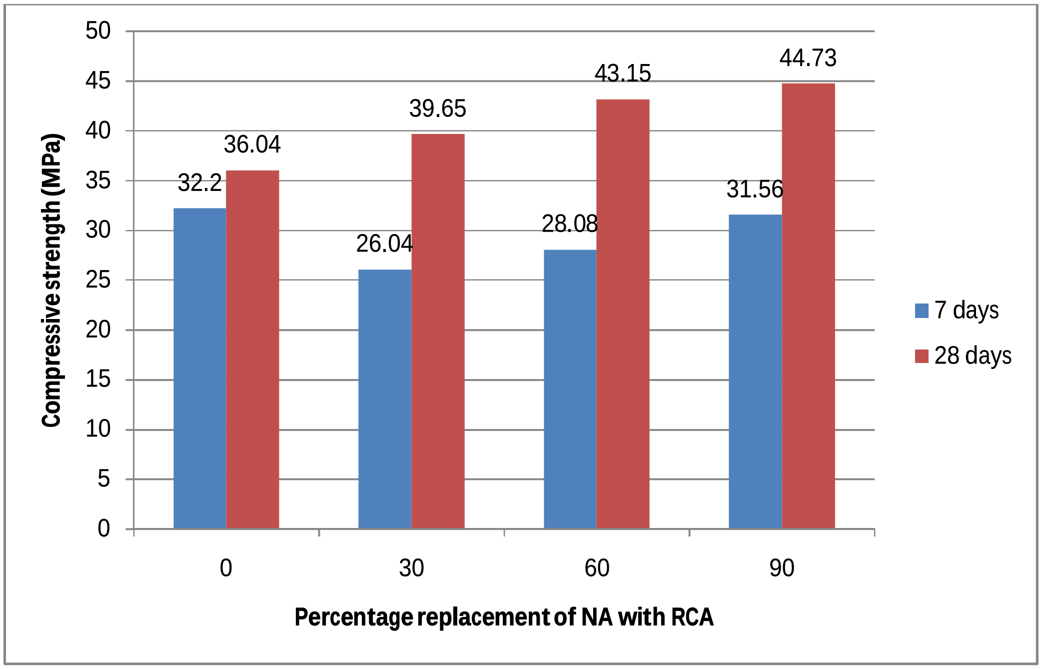

Figure: 4.3: 7 and 28 days compressive strength for w/c ratio 0.48

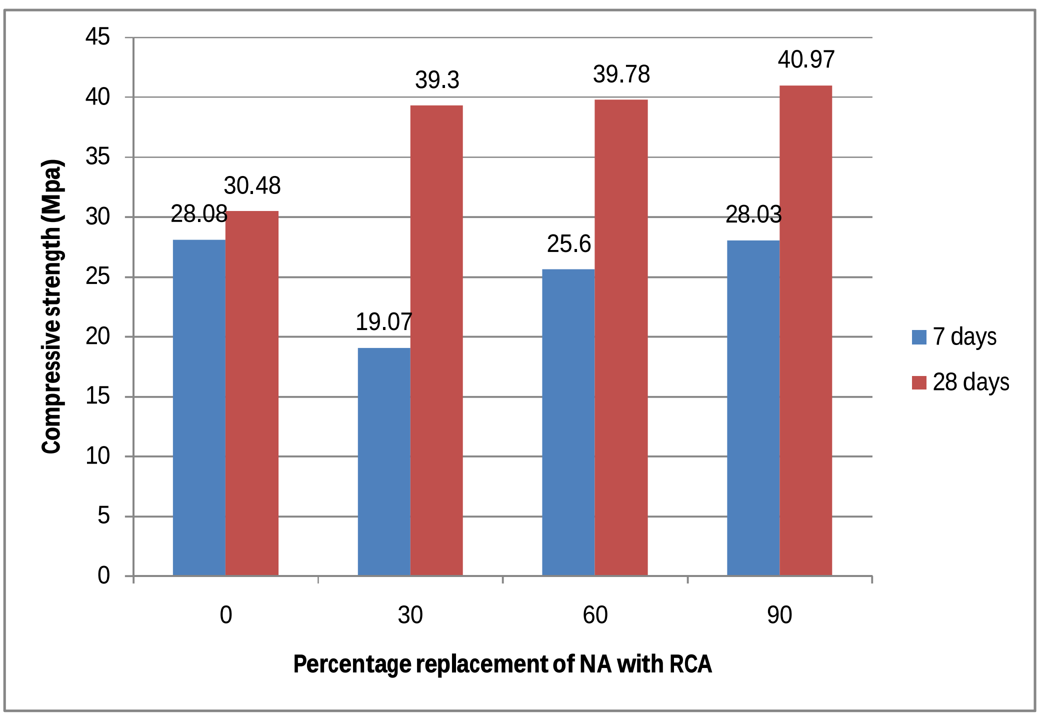

Figure: 4.4: 7 and 28 days compressive strength for w/c ratio 0.51

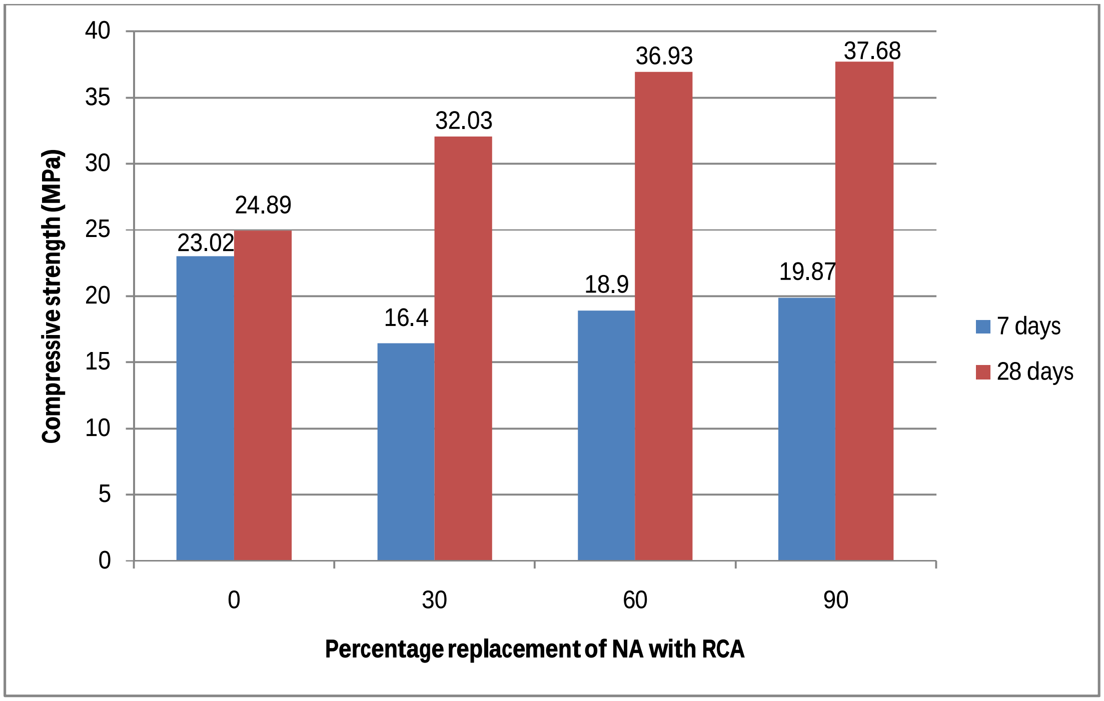

Figure: 4.5: 7 and 28 days compressive strength for w/c ratio 0.55

Therefore, the bond between recycled aggregate and new concrete paste has not developed yet. The failure in this case will occur in the interfacial transition zone (ITZ) which is weaker in recycled coarse aggregate concrete as is observed by Xiao et al, (2012).

This trend of decrease in strength is very prominent at 30% replacement level. It may be due to at 30% replacement level, we have concrete with two types of aggregates (i.e. natural and recycled) therefore, and at this level interfacial transition zone is of mixed characteristic, which is rather playing a negative role in overall behaviour of concrete. It can be concluded that if recycled coarse aggregate are used, they must be used at higher replacement levels. Infact, 90% replacement levels gives the maximum efficient at 28 days.

As we increase the recycled aggregate content the, 28 day compressive strength increase. It is because at high recycled aggregate content, these aggregate absorb more water.Therefore, the effective water- cement ratio decreases and hence the strength increases. The similar trend is observed by Butler et al. (2011).On the basis of microstructure studies, they further concluded that recycled coarse aggregate improve the interfacial transition zone between the new mortar and aggregate. This improvement is due to more roughed surface texture of recycled coarse aggregate particles as compare to natural aggregate.

Also, the hydration products formed will penetrate deep into the cracks of recycled coarse aggregate, thus improves the ITZ further. Similar observation was made by Kou et al.(2011) when recycled coarse aggregate was used along with various mineral admixtures.

4.2.2 Effect of water-cement ratio on compressive strength

From Figure 4.1 -4.5, it can be seen that as water-cement ratio decreases, compressive strength increases. Rate of increase of compressive strength for recycled coarse aggregate concrete with water-cement ratio is not as high as the corresponding rate when only natural aggregate are used. It is because strength gain with the use of recycled aggregate is very high at higher water-cement ratios. And as the water-cement ratio reduces, the strength gain is not very prominent as can be seen from figure 4.2. Similar trend was obtained by Rahal (2007).

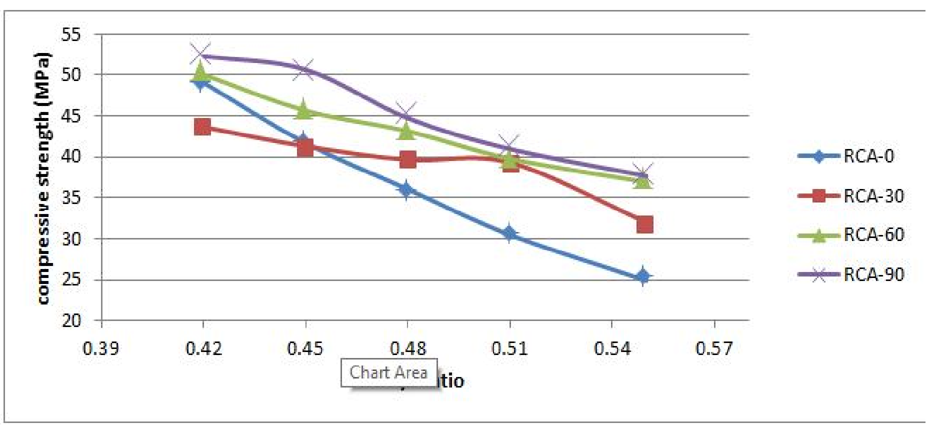

Figure 4.6: 28 days compressive strength versus w/c ratio

4.3 BOND STRENGTH

Two cubes for each batch of concrete mix are casted and cured for 28 days in order to determine bond strength of all the mix concrete. The mixes are casted at water-cement ratio 0.42, 0.45, 0.48, 0.51 and 0.55. Table 4.2 shows bond strength of cubes tested at 28 day curing. The data is further represented systematically in the form of bar graphs as shown in Figure 4.7. Bondstrength between concrete and deformed steel bars increases as percent of recycled aggregate increases. The results obtained are discussed in the following sections:

4.3.1 Effect of RCA on Bond Strength

As can be seen from Figure 4.7, with the increase of recycled coarse aggregate replacement initially bond strength decreases and then increases. Bond strength is maximumat coarse aggregate replacement level of 90%. Similar trend is observed at all water-cement ratios. This increase in bond strength is may be due to same modulus of elasticity of recycled coarse aggregates and the cement paste of recycled coarse aggregate concrete which at the level of concrete microstructure should improve composite action between these two phases and reduce incompatibilities of deformations under applied loads as suggested by Poon et al. (2004).

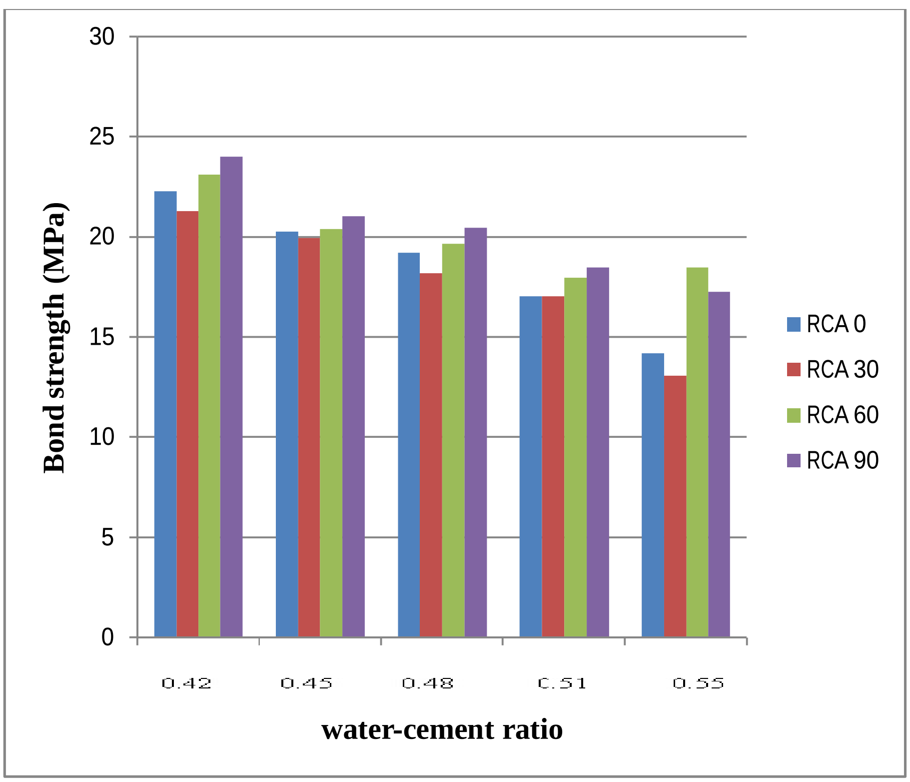

Figure 4.7: Variation of bond strength with RCA replacement percentage for all w/c ratios

Table 4.2: Experimental results of the pull out test specimen

Specimen ID	Replacement ratio	Water-cement ratio	Pull out load (KN)	Bond strength (MPa)
A1-0	0	0.42	84.64	22.29
A1-30	30		84.65	21.05
A1-60	60		93.03	23.134
A1-90	90		96.53	24.0
A2-0	0	0.45	81.51	20.07
A2-30	30		80.25	19.95
A2-60	60		82.0	20.39
A2-90	90		84.55	21.02
A3-0	0	0.48	77.25	19.21
A3-30	30		73.16	18.19
A3-60	60		79.10	19.67
A3-90	90		82.20	20.44
A4-0	0	0.51	68.50	17.03
A4-30	30		64.12	15.94
A4-60	60		72.25	17.96
A4-90	90		74.25	18.46
A5-0	0	0.55	57.13	14.20
A5-30	30		52.50	13.05
A5-60	60		67.16	16.70
A5-90	90		69.52	17.28

In order to study the effect of type of aggregate only, many researchers have suggested the use of normalized bond strength instead of bond strength [Xiao et al. (2007)], [Prince and Bhupinder(2012)].

Normalized bond strength (τ_n) is defined as the ratio of mean bond strength (τ) to the square root of compressive strength (f_c).

$$Normalized\ Bond\ Strength(\tau_n)=\frac{\tau}{\sqrt{f_c}}$$

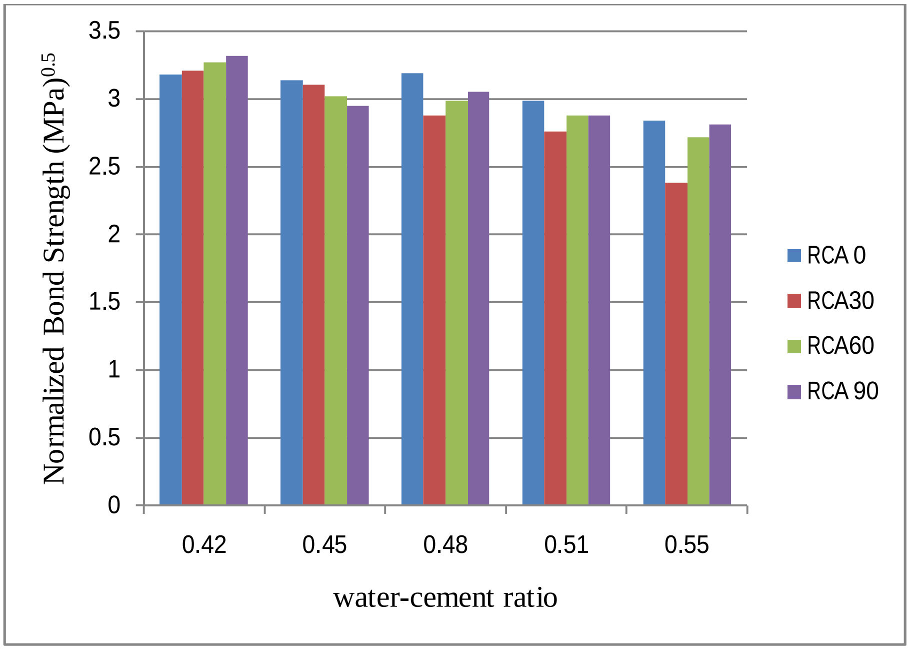

Figure 4.8: Variation of normalized bond stress with recycled coarse aggregate replacement ratio.

From the Figure 4.8, it can be concluded that the normalized bond strength remains almost unaffected by the replacement of coarse aggregate.

4.3.2 Effect of water-cement ratio on Bond Strength

From Figure 4.7 we can observe that bond strength depends on water-cement ratio. As water-cement ratio decreases bond strength increases. The bond strength increased as the w/c ratio decreased. This may be because the bond strength between recycled coarse aggregate concrete and the rebar depends on the concrete type and properties, mechanical anchorage and friction resistance. That is, concrete type and properties are different according to the recycled aggregate used, and this difference changed the mechanical anchorage and friction resistance between the two materials. The bond strength can therefore be considered to be strongly influenced by recycled aggregate ratio, among numerous other factors.

4.4 RELATION BETWEEN BOND STRENGTH AND COMPRESSIVE STRENGTH

In order to see that if any relation exists between bond strength and compressive strength of recycled coarse aggregate, Figure 4.9 is plotted containing all the data obtained from previous tests. From the best fit line the following relationship is observed.

$$\text{Bond strength} = 1.1244(\text{compressive strength})^{0.7639}$$

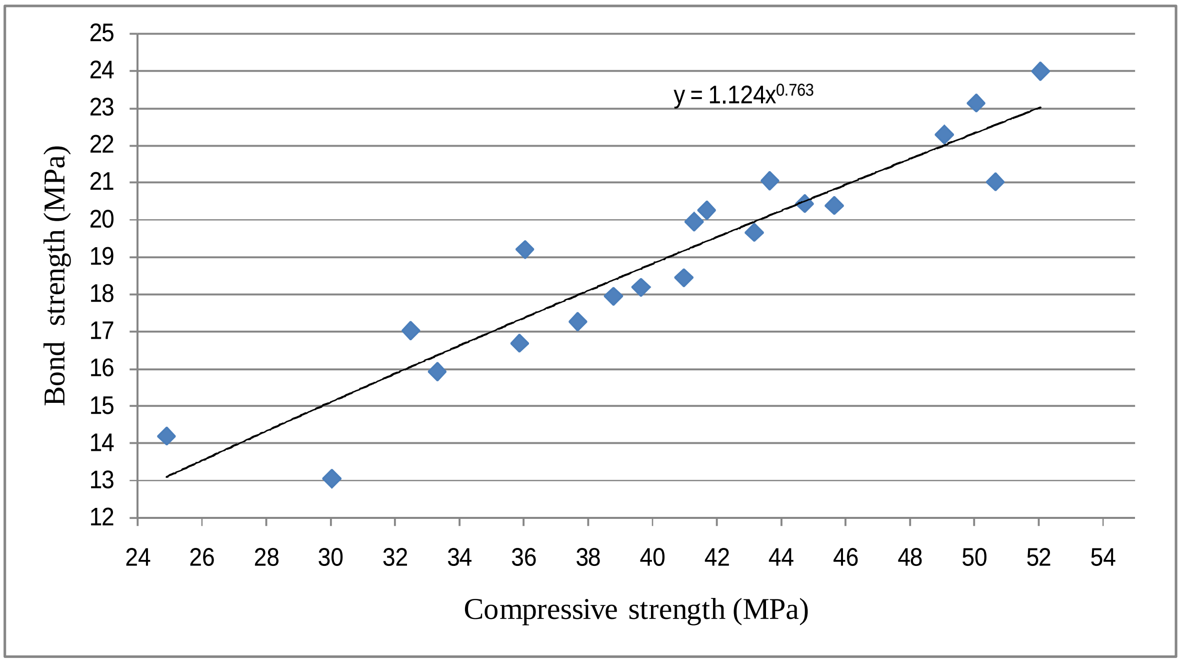

Figure 4.9: Relation between bond and compressive strength

The data points compared with the models already existing in literature i.e. ACI 408 model and Ogura- Koichi model (Figure 4.10). From Figure 4.10 it is observed ACI 408 model highly underestimates the value of bond strength. Ogura – Koichi model also underestimate the values but to the lesser extent.

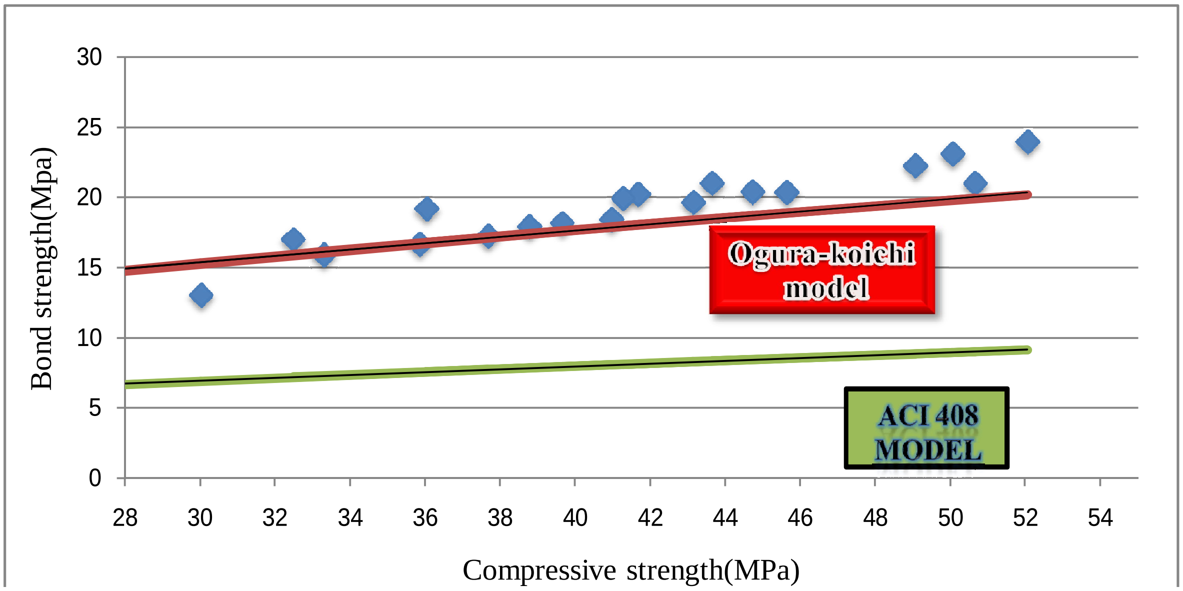

Figure 4.10: Comparison of experimental values with predicted models available on bond strength

Therefore, if the square – root model is to be followed to calculate the values of lap length and anchorage length of reinforced concrete structure Ogura – Koichi model will be more economical.

CHAPTER 5
CONCLUSION

5.1 INTRODUCTION

The reuse of recycled materials derived from construction and demolition waste is growing all over the world. One of the most environmentally responsible ways of meeting the challenges of sustainability in construction is the use of recycled aggregates in new construction. The main objective of the PRESENT work is to investigate the effect of using recycled aggregates in lieu of natural aggregate on compressive strength and bond strength of concrete.The major observations from this experimental work are as under:

5.2 MAIN CONCLUSIONS OF THE STUDY

- The 28 day compressive strength of concrete increases as the percentage of recycled aggregate. Increase in compressive strength for 28 days for 90% replacement of coarse aggregates are 7.92%, 21.54%, 24.54%, 24.11%, 34.41 and 51.38% for water ratio 0.42, 0.45, 0.48, 0.51, 0.55 respectively. It shows that major advantage of using recycled aggregates is achieved in low strength concretes made with higher w/c ratio.

- The bond strength of concrete decreases for 30% replacement and afterwards it increases. Bond strength is maximum at 90% replacement. Increase in bond strength at 90% replacement level is 7.67, 3.70, 6.40, 8.39 and 21.69 for respective water-cement ratio 0.42, 0.45, 0.48, 0.51 and 0.55.

- Recycled aggregate must be used at higher replacement levels. At this level, maximum benefit in terms of compressive strength and bond strength are achieved.

- A power series relationship exists between compressive strength and bond strength of recycled aggregate concrete. The existing models proposing the square root law underestimates the bond strength of concrete.

REFERENCES

Adnan S. H, Rahman I. A, Saman H. M. (2011) “ ASEAN Australian Engineering Congress”, Kuching, Sarawak, Malaysia

Ajdukiewicz, A. and Kliszczewicz, A. “Influence of Recycled Aggregates on Mechanical Properties of HS/HPC”. *Cement and Concrete Composites*, Vol. 24, 2002, pp. 269 – 279.

Butler L., 2012, “Evaluation of Recycled Concrete Aggregate Performance in Structural Concrete”, thesis, The University of Waterloo, Canada, Viewed April 2013

Butler L., West J.S., Tighe S.L., 2011. “The effect of recycled concrete aggregate properties on the bond strength between RCA concrete and steel reinforcement” , Cement and Concrete Research 41 (2011) 1037–1049

CE-04014, “Design of concrete structure”, Department of technical and vocational education, Ministry of Science and Technology.

Choi H.B, Kang K.I, 2008. “Bond behaviour of deformed bars embedded in RAC”, Magazine of Concrete Research, 2008, 60, No. 6, August, 399–410

Desnerck P, Schutter G. D., Taerwe L., 2010. “Bond behaviour of reinforcing bars in self-compacting concrete” experimental determination by using beam tests, Materials and Structures (2010) 43:53–62

DG/TJ08-2018-2007. Technical Code for Application of Recycled Concrete (in Chinese). 2007

Fathifazl, G. “Structural Performance of Steel Reinforced Recycled Concrete Members”, PhD Thesis, Carleton University, Ottawa, Ontario, Canada, 2008, 504 pgs.

Gonzalez-Fonteboa and Martinez-Abella,. “Shear Strength of Recycled Concrete Beams”, *Construction and Building Materials*, Vol. 21, 2007, pp. 887 – 893.

Harajli M. H., Hamad B. S., and Rteil A. A., 2004, “Effect of Confinement on Bond Strength between Steel Bars and Concrete”, ACI Structural Journal/September-October 2004

Husem Metin, 2003. “The effects of bond strengths between lightweight and ordinary aggregate-mortar, aggregate-cement paste on the mechanical properties of concrete”, Materials Science and Engineering A363 (2003) 152–158

IS 2770 (Part I) (1967) (Reaffirmed 2002) “Methods of testing bond in reinforced concrete. Part I: Pull-out test”. Bureau of Indian Standards, New Delhi, p 10.

IS 8112 (1989) (Reaffirmed 2005) 43 Grade ordinary Portland cement-specification. Bureau of Indian Standards, New Delhi, p 8

Wight K. J, MacGregor J.J, “Reinforced Concrete Mechanics and Design”, fifth edition, PEARSON Prantice Hall , Upper Saddle River, New Jersey,2009

Khatib, J.M., 2005. Properties of Concrete Incorporating Fine Recycled Aggregate.Cement and Concrete Research, V. 35, pp.763-69.

Rakshvir M., Barai S. V., 2006, “Recycled aggregates-based concrete”. Waste Management & Research, Vol. 24, No. 3, 225-233,

Neville, A.M., 1995. “Properties of Concrete”UK: Longman. p844.

Poon, C. S., Kou S. C., Lam, L., 2007. “Influence of Recycled Aggregate on Slump and Bleeding of Fresh Concrete”. Materials and Structures, V. 40(No. 9), pp981-88.

Poon, C.S. et al., 2004. “Influence of Moisture States of Natural and Recycled Aggregates on the Slump and Compressive Strength of Concrete”. Cement and Concrete Research, V. 34, pp31-36.

Rahal, K., 2007. “Mechanical Properties of Concrete with Recycled Coarse Aggregate. Building and Environment”, V. 42, pp407-15.

RILEM. “Specifications for concrete with recycled aggregates”. Mater Structure, 1994, 27: 557–559.

Tu, T.Y., Chen, Y.Y. & Hwang, C.L., 2006. “Properties of HPC with Recycled Aggregates”. Cement and Concrete Research v.36 (pp943-950).

Xiao Jianzhuang, Falkner H., 2007. “Bond behaviour between recycled aggregate concrete and steel rebars”. Construction and Building Materials 21 (2007) 395–401.

Yang, K.-H., Chung, H.-S. & Ashour, A.F., 2007. “Influence of section depth on the structural behaviour of reinforced concrete continuous deep beams”. Magazine of Concrete Research, 59(8), pp.575-86.

Y.H., Tyan, Lin, Y.Y., Chang, T.P. & Chang, C.Y., 2004. “An Assessment of Optimal Mixture for Concrete Made with Recycled Concrete Aggregates”. Cement and Concrete Research, V. 34, pp.1373-80.

Yanagibashi, Morohashi., and Sakurada. 2007, “Bond Splitting Strength of High quality Recycled Coarse Aggregate Concrete Beams, Journal of Asian Architecture and Building Engineering”, vol.6 (2) 331-337.

Xu Y. Z., Shi J G. “Analyses and evaluation of the behaviour of recycled aggregate and recycled concrete” (in Chinese). Chinese Concrete Journal, 2006, 7: 41–46.

Xiao J Z. Recycled Concrete (in Chinese). Beijing: “Chinese Building Construction Publishing Press”, 2008.

http://www.slideshare.net/abhiktushardas/cement-industry-analysis

www.ies.org.sg