

**MECHANICAL AND DURABILITY PROPERTIES OF CARBONATED  
RECYCLED AGGREGATE CONCRETE**

*A Thesis submitted in fulfillment of the requirement for the award of the degree of*

**MASTER OF ENGINEERING**  
**in**  
**STRUCTURAL ENGINEERING**

Submitted By

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**JULY, 2018**

## DECLARATION

I, **Harsimranjit Singh**, hereby declare that the work presented in this thesis entitled "**Mechanical and Durability Properties of Carbonated Recycled Aggregate Concrete**" in fulfilment of the requirement for the award of the degree of **Master of Engineering in Structural Engineering** submitted at **Civil Engineering Department, Thapar Institute of Engineering & Technology, Patiala**, is an authentic record of work carried out by me under the supervision of **Dr. Shakeel Ahmad Waseem**, Assistant Professor, Civil Engineering Department, Islamic University of Science & Technology, Jammu and Kashmir and **Dr. A.B Danie Roy**, Assistant Professor, Civil Engineering Department, Thapar Institute of Engineering & Technology, Patiala.

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## CERTIFICATE

This is to certify that the thesis entitled "**Mechanical and Durability Properties of Carbonated Recycled Aggregate Concrete**" being submitted by **Harsimranjit Singh**, Roll No: **801624010** in fulfilment of the requirement for the award of the degree of **Master of Engineering in Structural Engineering** is a bonafide work carried out by him under my guidance and that no part of this thesis has been submitted for award of any other degree.

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## **ACKNOWLEDGEMENT**

Before we get into the midst of the things, I would like to express my appreciation for the people who were involved in this thesis work right from the day of its commencement. Writing of this thesis has been a learning experience involving many challenges which I would not have been able to overcome without the support, assistance and patience of the various helpful persons involved. It is to them I owe my heartfelt gratitude and respect.

I feel utterly delighted to put forward my project report on “**Mechanical and Durability Properties of Carbonated Recycled Aggregate Concrete**”. I feel privileged for having helpful people who have been of great assistance to me in bringing this work to its fruitful conclusion. The successful finalisation of this thesis is the sheer result of extensive labour and determination put in by myself with the help of my project guides. I hereby take this opportunity to add special note of thanks for **Dr. Shakeel Ahmad Waseem, Assistant Professor, Civil Engineering Department, Islamic University of Science & Technology, Jammu and Kashmir** and **Dr. A.B Danie Roy, Assistant Professor, Civil Engineering Department, Thapar Institute of Engineering & Technology, Patiala** who undertook to act as a mentor to myself despite their many other professional commitments. Their knowledge, wisdom and patience to highest standards has motivated and has been an inspiration to reach for my goals. Without their vision, encouragement and uncanny guidance this thesis would not have reached its fruitfulness.

I would also like to thank all the friends, staff members and lab assistants for providing with all the help and facilities, which I required for the completion of this thesis report.

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## **ABSTRACT**

Concrete has been proved very commonly used and a leading construction material all around the world for a period of more than a century due to its durability, satisfactory compressive strength, versatility, availability and cost-effectiveness. Around the world, the concrete industry is using the large amounts of natural resources, as a result of this, they are now becoming insufficient to fulfil the increasing demands of industry. Also, the utility of old structures is decreasing, so these structures are demolished to make a way for modern construction. Concrete wastes can be used for making RCA's after the process of crushing and sieving. These aggregates can be obtained from many sources like demolition waste, construction waste & industrial waste etc. Also, the mechanical & durability properties of the recycled aggregate concrete are weaker than that of normal concrete, due to the mortar attached having a large number of pores or the cracks that form during crushing.

Hence, if the attached cement mortar can be improved, then it will increase the applications of RCA. The various methods that can be used to improve the quality of recycled concrete aggregate include mechanical grinding, heat & rubbing method, pre-soaking in acid, two-stage mixing approach, self-healing, ultrasonic cleaning, mineral admixture solution and carbonation method.

Therefore, the main objective of this thesis is to improve the quality of recycled concrete aggregates (coarse) by using the "Carbonation" technique and after making the concrete by using these treated aggregates, the Non-destructive, Mechanical and Durability properties of normal concrete, recycled aggregate concrete and carbonated recycled aggregate concrete are compared. A total of three mix combinations named NAC (using 100% natural coarse aggregate), RAC (using 100% recycled coarse aggregate) and CRAC (using 100% carbonated recycled coarse aggregate) were prepared using w/c ratio of 0.48. It has been found that by using the carbonated recycled concrete aggregates (CRCA), RAC's non-destructive, mechanical and durability properties can be improved because the method of carbonation not only refine the RCA's properties, also it reduces the greenhouse effect which is originated by CO<sub>2</sub> emission. Also, this method used is lower in cost and more environment-friendly than other methods. Due to carbonation of recycled concrete aggregates (RCAs), there is an improvement shown in non-destructive properties like an ultrasonic pulse velocity, rebound hammer; in mechanical properties like an increase in compressive strength, flexural strength, split tensile strength and in durability properties like a decrease in rapid chloride permeability, water absorption, water permeability, sorptivity.

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# CHAPTER 1

## INTRODUCTION

### 1.1 GENERAL

Concrete has been proved very commonly used and a leading construction material all around the world for a period of more than a century due to its durability, satisfactory compressive strength, versatility, availability and cost-effectiveness. Main ingredients of the concrete are cement, fine aggregates (like sand), coarse aggregates (of different sizes like 10 mm and 20 mm maximum size) and water. Among to these ingredients, aggregates (both fine and coarse) covers about 70-80% of the volume of concrete. But it is not an environment-loving material, because it utilizes large amounts of natural aggregates and also after demolishing of buildings, it reaches to the landfills and occupies a large space of the land. In the past years, due to faster growth in the urbanisation & industrialization has caused in a great demand for concrete worldwide. It is estimated that 1 m<sup>3</sup> per capita of concrete is produced annually around the world (*Ozbakkaloglu et al., 2017*).

Around the world, the concrete industry is using the large amounts of natural resources, as a result of this, they are now becoming insufficient to fulfil the increasing demands of industry. Also, the utility of old structures is decreasing, so these structures are demolished to make a way for modern construction.

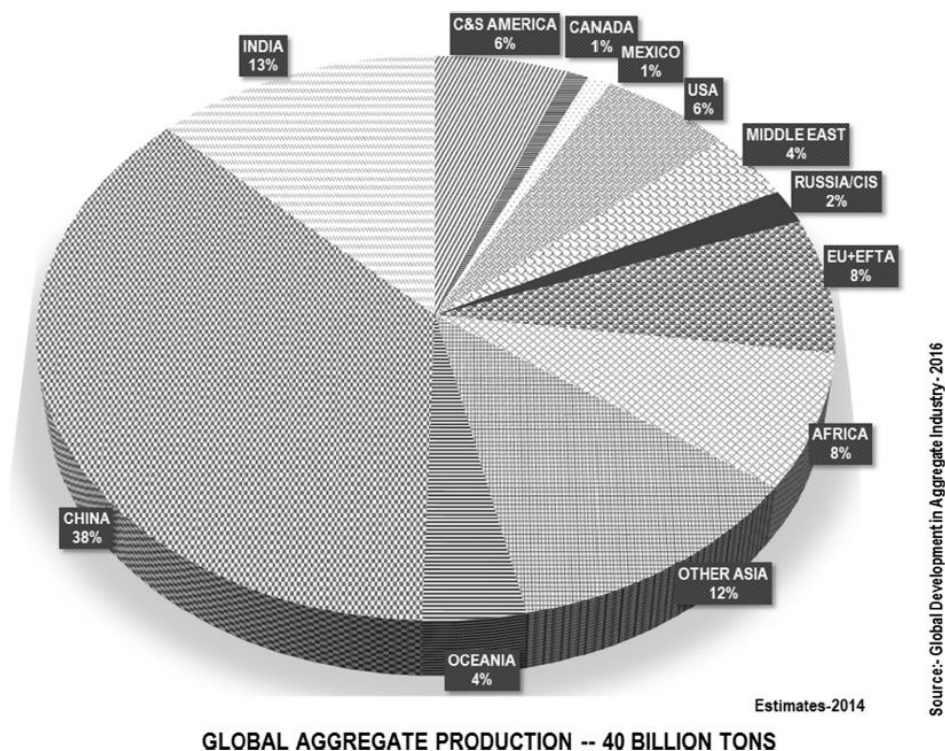


**Figure 1.1:** Debris of concrete after the demolition of the structure, ([www.happho.com/recycled-aggregate-concrete-applications-advantages-disadvantages-construction/](http://www.happho.com/recycled-aggregate-concrete-applications-advantages-disadvantages-construction/))

Structures are demolished because of many reasons like natural disasters, world-war damages, and new construction for improved economic gains. Demolition of structures is increasing every day. It is estimated that every year worldwide over 1 billion tonnes of concrete wastes and construction & demolition wastes (C&DW) are generated (*Amor and Rachida, 2017*).

USA is one of the biggest producers in the world for the C&DW, generating greater than 500 million tonnes annually. In Europe, France is the biggest producer of C&DW around 246 million tonnes until 2012. In Asia, China is the largest producer of C&DW around 1 billion tonnes until 2012. Also, India generates around 530 million tonnes of C&DW which makes India, the second largest producer of C&DW in the world. Many countries such as USA, Germany, U.K, and Japan have successfully utilized the C&DW nearly around 90%, However, in India, fewer efforts are reported about the recycling of demolition wastes (*Ali and Ajit, 2018*).

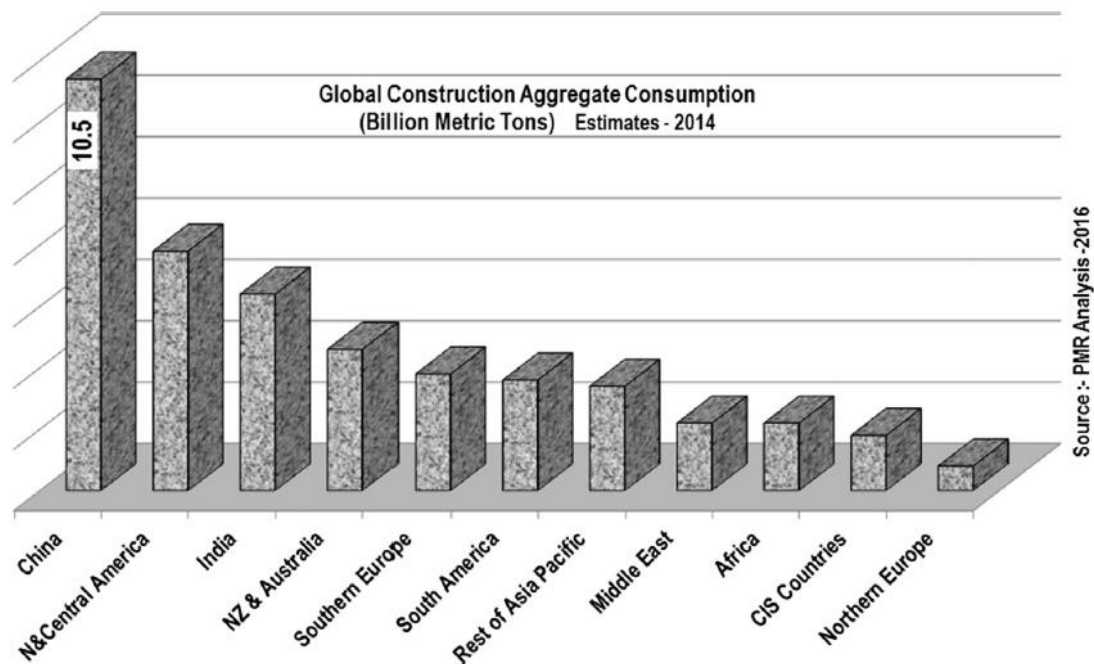
Due to the continuous population growth, house building activities, construction of infrastructure, industrial development, very large amounts of C&DW has been generated and hence, now it needs for recycling this waste. The construction industry is the main user of the natural resources and worldwide aggregate production becomes almost doubled from the 21 billion tonnes in the year 2007 to 40 billion tonnes in the year 2014 (*Tam et al., 2018*).



**Figure 1.2: Natural Aggregates production by various countries around the world in the year 2014, (*Tam et al., 2018*)**

Countries like China, India, Gulf States, Indonesia, Russia, Mexico, Turkey, Brazil, Thailand, Malaysia have recorded strongest increases in demand for recycling this waste (Tam et al., 2018). Also, large amounts of natural aggregates are produced for construction applications every year resulting in the large-scale depletion of natural resources.

With more special importance on reducing carbon footprint, in the construction industry, recycling of concrete from demolishing of old structures is now coming into practice. The first initiatives for recycling and reducing the C&DW began in the decade of 1980 (Tam et al., 2018). Earlier, the concrete waste used to be dumped into landfills, but now it is being utilized as a coarse aggregates replacement in the concrete mix. Also, the cost for dumping this debris is increasing because the appropriate sites are not available nearby. Apart from the scarcity of land, other problems related with landfill includes public opposition, transportation cost and silting. New Zealand has introduced an act called “waste minimization act 2008” to minimize the landfill sites waste disposal and to increase the recycle & reuse of waste streams (Ali and Ajit, 2018).

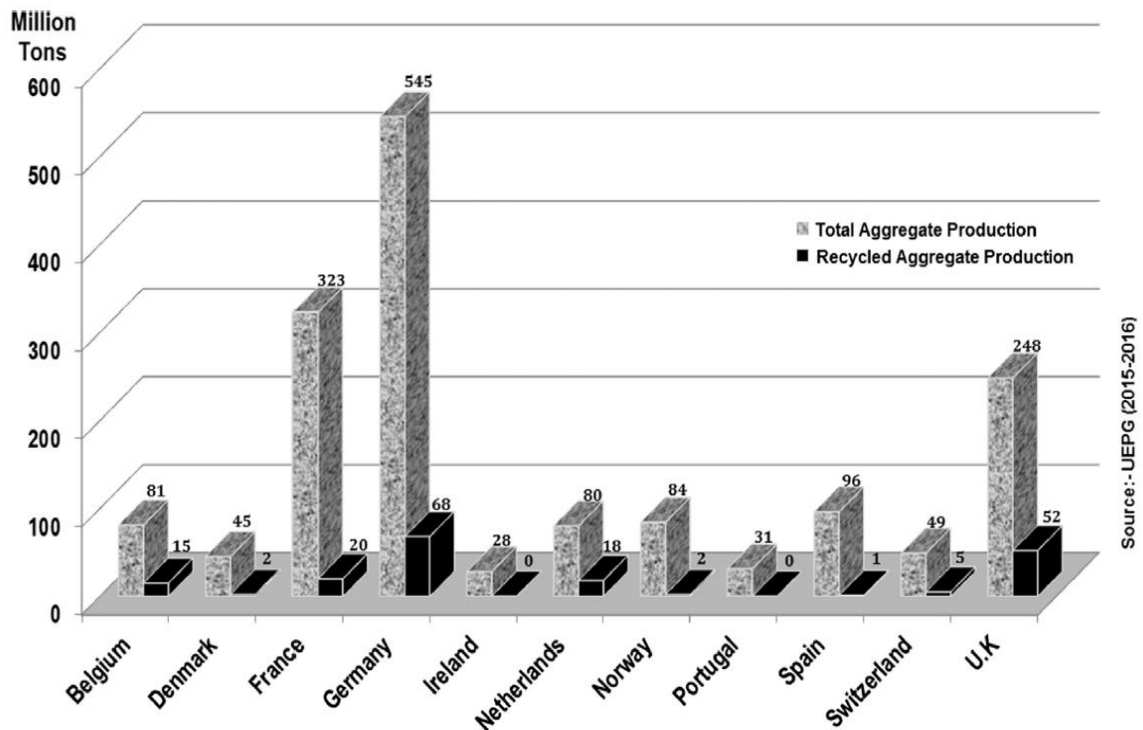


**Figure 1.3: Estimates of the global recycled aggregate consumption (by regions), (Tam et al., 2018)**

To reduce the energy and raw materials consumption is a major issue for the world at present. Thus, recycling of waste concrete has been gaining a good attention in the construction industry over the past few years. Coarse aggregates are one of those materials that can be recycled from the demolished structures. Using the recycled coarse aggregates in concrete mixes because of awareness of society for the protection of natural resources & for the effective use of concrete

waste materials. In eastern & western countries like Korea and Japan, there is increasing emphasis on the usage of coarse recycled aggregates for production of new concrete. But in India, there is relatively less awareness regarding the potential use of such aggregates. In India, the concrete waste is still dumped on landfill sites which occupy the large land area. Because sources of natural aggregate are not inexhaustible, therefore it is crucial to creating awareness regarding the potential usage of recycled coarse aggregates for production of concrete in India (Das et al., 2010).

Recycled aggregates can be obtained from the existing concrete, and therefore known as Recycled concrete aggregates (RCA). Concrete wastes can be used for making RCA's after the process of crushing and sieving. These aggregates can be obtained from many sources like demolition waste, construction waste & industrial waste etc. The properties of the recycled aggregates may depend on various factors like gravel fraction, the characteristic strength of old concrete, the percentage of sand and the size of gravel used in concrete mix. The use of RCA's can result in a reduction in compressive strength up to 40%, but for environmental & economic reasons, also due to increased amount of production of RCA's, there has been a growing worldwide interest in increasing the utilization of RCA's in construction applications (Tam et al., 2018).



**Figure 1.4: Total aggregate production vs recycled aggregate production comparison of various European countries in the year 2015, (Tam et al., 2018)**

Also, the mechanical & durability properties of the recycled aggregate concrete are weaker than that of normal concrete, due to the mortar attached or the cracks that form during crushing. The attached mortar to the RCA's came from the original concrete, plays a crucial role in performance determination regarding strength & permeability. Full replacement of natural aggregates by recycled concrete aggregates may not be suitable for all types of construction works, but up to a certain amount of RCA's use in new construction will be suitable as it does not significantly decrease the concrete strength (*Ozbakkaloglu et al., 2017*). Recycling of aggregates from the concrete waste can help to preserve land, reduce concrete waste, reduce energy consumption and also conserve natural resources. Recycling is only a single step for conserving natural aggregate resources, reducing the use of aggregates can be another step for conserving natural resources.

## 1.2 CURRENT APPLICATION OF RCA

In Singapore, the J-Cube Capital Mall (completed in 2011) is an example of the usage of recycled coarse aggregate in concrete in the structural application. It is built on site of demolished Jurong Entertainment Centre. This mall utilized the demolished concrete waste as the recycled coarse aggregate in 50% of the new concrete production ([www.ies.org.sg](http://www.ies.org.sg)).



**Figure 1.5: Shows the front view of the 200,000 ft<sup>2</sup> J-Cube Capital Mall, Singapore, (<https://it.pinterest.com/pin/454933999828572903/>)**

Another example came from North America, where the former Stapleton Airport in Denver, Colorado was demolished from which the 2100 tonnes of recycled concrete (from places like offices, old runways, and warehouse structures etc.) were utilized in the construction of new

Enterprise Park situated at Stapleton (2008). Total of 4300 m<sup>3</sup> of recycled concrete containing 1400 tonnes of RCA's was used for the construction of tilt-up wall panels, which makes it the biggest usage of recycled concrete in the tilt-up application ([www.etkinjohnson.com](http://www.etkinjohnson.com)).



**Figure 1.6: Shows the Enterprise Park situated at Stapleton, Denver, United States, ([www.etkinjohnson.com](http://www.etkinjohnson.com))**

Another example of the use of RCA's is the BRE office Building situated in Watford, UK (1996). More than 1500 m<sup>3</sup> of RAC supplied for structural columns, foundations, floor slabs and waffle floors ([www.projects.bre.co.uk](http://www.projects.bre.co.uk)).



**Figure 1.7: Shows the front view of the BRE office Building, Garston, Watford, UK, (<https://fcstudios.com/work/view/new-environmental-office-bre>)**

The Vilbeler Weg office building situated in Darmstadt, Germany (1998) is known for its usage of Recycled concrete aggregates (RCA's) in the construction. It has used approximately 480 m<sup>3</sup> of Recycled aggregate concrete (RAC) (Marinkovic *et al.*, 2002).



**Figure 1.8: Shows the Vilbeler Weg office building, Darmstadt, Germany, ([www.b-i-m.de/projekte/projframe.htm](http://www.b-i-m.de/projekte/projframe.htm))**

RCA had been used in New High School construction, outside the Oslo city, Norway in 2001. For foundations, half of columns and basement walls, 35% of natural coarse aggregates had replaced by RCA ([www.irbnet.de](http://www.irbnet.de)).



**Figure 1.9: RCA use in New High School construction in Sorumsand, Oslo, Norway, ([www.irbnet.de](http://www.irbnet.de))**

### **1.3 CLASSIFICATION OF RECYCLED AGGREGATES**

The following is the classification of the recycled aggregates :

- Recycled Concrete Aggregate (RCA) – It includes the crushed clean and sound concrete waste which is having total contamination of less than 1% of the bulk mass and of at least 95% by concrete weight.
- Recycled Concrete & Masonry (RCM) – It includes the graded aggregate that is produced from the clean and sorted waste concrete and masonry.
- Reclaimed Aggregate (RA) – It includes coarse aggregate that is reclaimed from the concrete that had been rejected by means of separating the aggregates from the slurry of water-cement.
- Reclaimed Asphalt Pavement (RAP) – It includes old asphalt concrete.
- Reclaimed Asphalt Aggregate (RAA) – It includes coarse aggregate that is reclaimed & asphalt granules that are recycled from the waste asphalt concrete.
- Glass Cullet – It includes glass cullet which is reduced to a sand-like product.
- Scrap Tyres – It includes an aggregate of crumb rubber and scrap tyres that are processed used as tyre chips.
- Used Foundry Sand – It includes spent foundry sand.

### **1.4 PRODUCTION OF RECYCLED AGGREGATES**

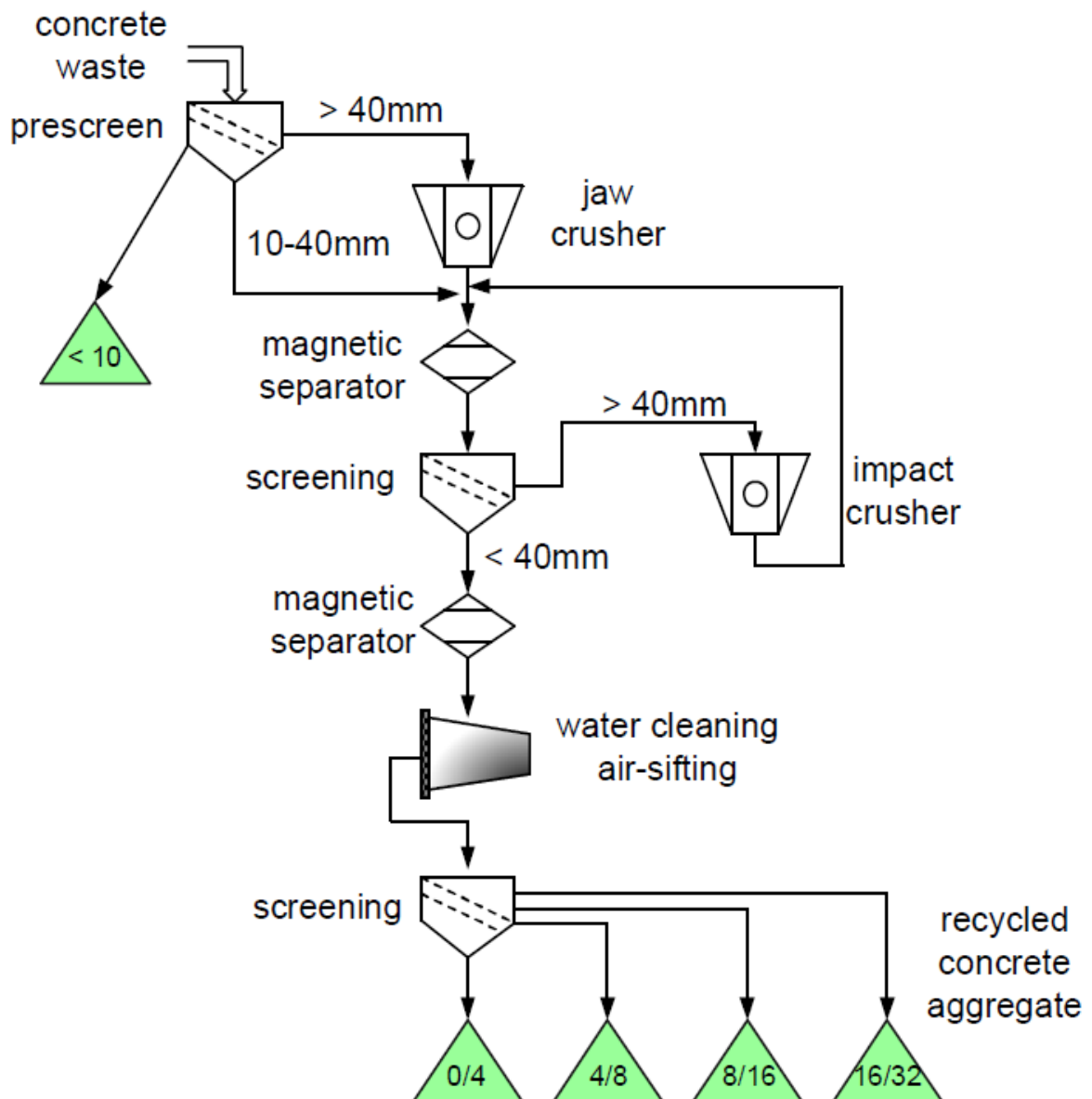
After the demolition of the concrete structure, large quantities of concrete waste are produced. To produce the recycled aggregates from this waste, normally recycling plants are used. These plants are located normally in suburbs of cities because the noise pollution during the recycling process made by the equipment's is very large.

The common machines that are used for the production process are impact crusher, mixing machines, jaw crusher, and screens for removing impurities. The first stage for production process includes sorting of demolition debris. In initial research, removal of steel from the concrete debris was a concern regarding the sorting of recycled concrete because there was a concern that the crushers can be damaged by the steel.

#### **(a) Stationary Recycling Plants :**

This process includes the two-stage crushing of concrete waste by jaw crusher & impact crusher and screening to remove the contaminants like wood, gypsum, reinforcement, plastics, paper, metals, glass, oil-droppings, plaster, waste electronic equipment etc. by various involved

processes like water cleaning, magnetic separation and air sifting. After all these processes, we get the recycled aggregates of different sizes like 0-4 mm, 4-8 mm, 8-16 mm, and 16-32 mm.



**Figure 1.10: The Flowchart of Stationary Recycling Plant, (Marinkovic et al., 2002)**

**(b) Mobile Recycling Plants :**

This type of plants is normally operated when the demolition sites having big quantities of homogeneous waste which can be reused on the construction site after processing. It involves an only one-stage crushing process.

The handling and storage is also an important area for recycled aggregates. Regarding the usage of recycled aggregate concrete and recycled aggregates, the Japanese standard states the following:

- (a) Recycled aggregates that are produced by different production methods and that are produced from the normal concretes that are of distinctly different qualities shall be stored separately.
- (b) Recycled aggregates shall be stored away from the aggregates that are of other types.
- (c) Recycled fine and recycled coarse aggregates shall be stored at different locations.
- (d) When the different qualities and types of recycled aggregates are produced, then the recycling plant should not process that material which is coloured like concrete rubble together with the brick rubble because it will cause the extra cost for the cleaning of processing units.
- (e) Recycled aggregate shall be transported and stored in that manner so that no breakage and segregation happen or otherwise it can cause to change in the quality of concerned recycled aggregates.
- (f) Recycled aggregates absorb a large amount of water; therefore, these should be used in the surface dry or saturated condition.



**Figure 1.11: Mobile Recycling Plant, (Marinkovic et al., 2002)**

### **1.5 ADVANTAGES AND DISADVANTAGES OF RCA**

The various advantages of recycled coarse aggregates are following ([www.happho.com](http://www.happho.com)):

- The need for producing the natural aggregates is reduced due to the usage of recycled coarse aggregates.
- Use of the recycled coarse aggregate provides stability in the environment.

- Due to the usage of recycled coarse aggregates in the concrete mix, the quantities of waste concrete delivered to a landfill is reduced.
- 90% less energy is used for the production of RCA than the Portland cement production.
- In the recycled aggregate concrete if finer fly ash is used, then it will give greater compressive strength.
- Recycled aggregates while they are crushed into smaller sizes, absorbs a large amount of CO<sub>2</sub> from the atmosphere. Hence, it reduces the CO<sub>2</sub> amount in the atmosphere.
- More employment opportunities have been created by this recycling industry.
- If used in the construction project, it can reduce the cost of the project.

The various disadvantages of recycled coarse aggregates are following (*www.happho.com*):

- Noise levels can be increased by the recycling plant operation.
- Lack of guidelines and specifications.
- Attached cement mortar increases its water absorption capacity and also have a negative impact on density.
- It decreases the quality of the concrete and also reduces concrete's workability.
- Its usage decreases the compressive strength of concrete.

## **1.6 SOME IMPORTANT POINTS REGARDING THE USE OF RECYCLED COARSE AGGREGATES**

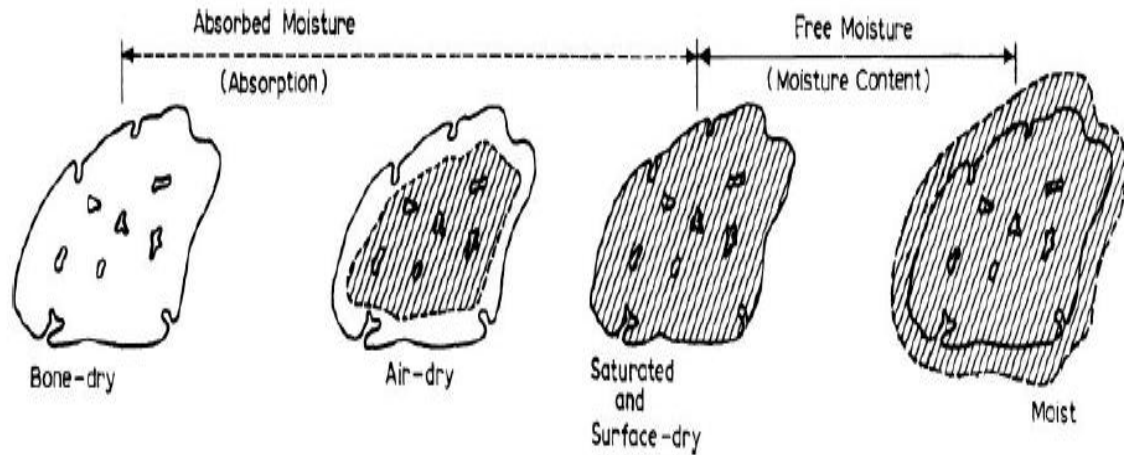
The various points that should be kept in mind during usage of recycled coarse aggregate in concrete are the following:

### **1.6.1 Absorption and Surface Moisture**

Normally, aggregates are the porous materials and some amounts of water can be absorbed on the surface of aggregates. The absorption capacity is normally described as the amount of water that is required to take the aggregate in the surface dry (SSD) condition. Aggregates can be in the various moisture states like air dry, moist state, oven dry or saturated surface dry states (*Neville, 1995*).

There is a difference between the aggregate absorbed moisture and the other additional water that is absorbed on the surface of the aggregate. In the concrete mixes, it is the free moisture or surface moisture which is used to balance the mixing water that is required. The moisture is utilized in water-cement ratio and only the free water is only present to mix in concrete. It is the number of internal pores that are present and size of pores which are responsible for aggregate water absorption and it is normally noticed that recycled coarse aggregates have

required more water than the normal ones because of the greater water absorption value of the attached mortar. The rate at which the absorption of water takes place plays an important role in concrete mix ratios, also in case of recycled coarse aggregates. Normally, it takes more time for absorbing moisture than natural ones, therefore, they cannot achieve the full saturation during the period of the mix. Hence, it is recommended that the recycled coarse aggregates should be pre-soaked to compensate for the slow absorption rate (Neville, 1995).



**Figure 1.12: Various moisture states of aggregates, (Neville, 1995)**

### 1.6.2 Adhered Mortar Content

After the concrete has been crushed, then the natural stone and attached old mortar only remain in the recycled coarse aggregate. This attached old mortar can occupy about 25-60% volume of the aggregate. It has been noticed that the fine recycled aggregates contain more adhered mortar content than the coarse ones. This residual mortar may have some negative effects on concrete properties like density, absorption, abrasion resistance etc.

The quantity of mortar that is present on the surface of recycled coarse aggregate largely depends on the process by which recycled aggregates are crushed. It has been observed that if uses the impact crusher, it produces large quantities of recycled coarse aggregates with less quantity of mortar attached to it. It is also suggesting that less strength is given by the adhered mortar in recycled coarse aggregate than the fresh mortar that is produced in new concrete. Hence, the weakest point in concrete produced by using coarse recycled aggregates is the attached mortar to recycled coarse aggregates (Etxeberria et al., 2007).

## 1.7 PROBLEMS ASSOCIATED WITH THE ACCEPTABILITY AND RE-USE OF RECYCLED AGGREGATE

Acceptability of recycled aggregate is disturbed because of the less confidence by customers in the products made up of recycled material and also because of the bad image linked with recycling activity (Tam et al., 2018). Even though in civil engineering construction, the recycled aggregates are being used in considerable amounts, it is still not easy to overcome the problems associated with recycled aggregates that prevent its wider use in construction as shown in Figure 1.13.



**Figure 1.13: Problems associated with the recycled aggregate that prevent its wider use in construction, (Tam et al., 2018)**

The various problems that are associated with the acceptability and re-use of recycled aggregate are following (Tam et al., 2018):

- i. The choice between the normal and recycled material mainly depends on the quality and price. The concrete's quality made up of recycled aggregate may be the same as

that of concrete made up of natural aggregates, but the recycled aggregate is considered with doubt. Therefore, recycled aggregate will only be preferred where such aggregate have a lower price than the natural aggregate.

- ii. An important barrier regarding the usage of recycled aggregates is the variation in its quality. The C&D processing plants can easily overcome this type of barrier.
- iii. Sufficient quantity of recycled aggregate must be present so that it can be utilized properly. This can become the primary reason to encourage the usage of recycled aggregate for builders and constructors.
- iv. Lack of processing facilities/infrastructure and well-developed collection are other problems that are associated with the increased usage of the recycled aggregate in construction.
- v. The trust of the user or customer is weak to recycled products, and there is a possibility that they will dislike the recycled products.
- vi. The higher quality concrete waste must be used as a recycled coarse aggregate, while the lower quality waste must be used as an aggregate in road base. When preparing a ready-mixed recycled concrete, the cost of recycled aggregate may significantly increase if the concrete made factory is constructed closely to the recycled aggregate factory for saving the transportation costs. As a result, there will be low motivation for concrete manufacturers and contractors for using recycled aggregates.
- vii. Another problem is the lack of commitment and government support regarding the development of the recycling industry.
- viii. Apart from the specifications of JIS, RILEM (RILEM, 1994) and those used in Hong Kong, code standards/specifications are very limited regarding the usage of recycled aggregates.
- ix. Some technical problems like weak ITZ between aggregate and cement paste, high content of cement mortar, high levels of chlorides & sulphates, high porosity, more cracks formed during crushing, poor grading, high variations in quality etc.

### **1.8 VARIOUS METHODS USED TO IMPROVE THE QUALITY OF RECYCLED CONCRETE AGGREGATE**

Recycled concrete aggregate (RCA) that are produced from the C&D waste normally consists of adhered mortar and natural coarse aggregate that makes it porous because of inhomogeneous nature, less dense and high mortar content attached. In the recycled aggregate, the volume of adhered mortar generally varies from 25-60% depends on the size of aggregate (*Despotovic, 2016*). Hence, if the attached cement mortar can be improved, then it will increase the

applications of RCA. The various methods that can be used to improve the quality of recycled concrete aggregate are the following:

- i. **Mechanical Grinding:** From the natural aggregate adhered mortar can be removed in large quantities by using the crushing and ball-milling method. This is a popular and simple treatment having a lot of variations. Also, the recycled concrete aggregate can be damaged (occurrence of micro-cracks) by mechanical grinding. In the autogenous cleaning process, firstly recycled concrete aggregates are put in a rotating mill drum, then rotation of mill drum starts and inside aggregates start colliding against each other and also removing the pieces of the residual mortar on aggregates. The mill drum is of 50 cm in depth and 30 cm in diameter.



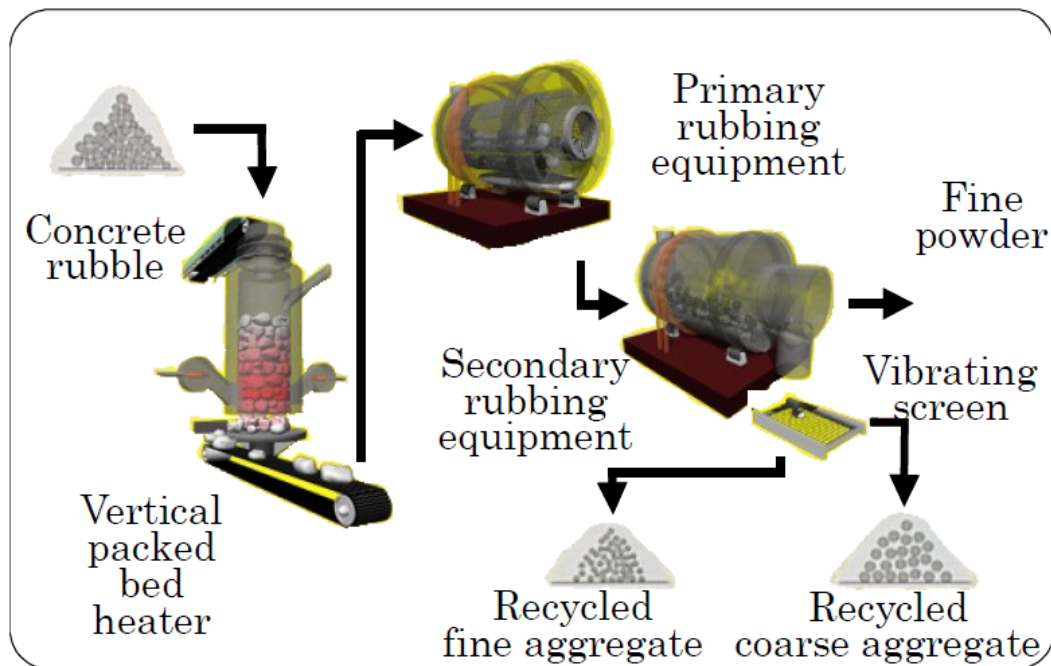
**Figure 1.14: The mill drum, (Despotovic, 2016)**

Up to 33% raw recycled aggregates can be filled in the drum and the rotation rate used for this process is 60 rotations per minute. After this process, water is used to clean the aggregates and then dried for removing all the produced impurities and fine remaining. The results of this process show a decrease in water absorption capacity of aggregate with increasing the time from 2 to 10 or 15 minutes, amount of water absorbed is decreased by 20% and 50%, the number of fine particles is also increased. Also, residual mortar content in uncleaned recycled aggregates shows about 30%, while cleaning of aggregates in this process shows a decrease in the residual mortar up to about 15% (Despotovic, 2016).

- ii. **Heat & Rubbing method:** In this method, the cement paste is changed to the brittle state by dehydration when the demolished concrete waste is heated up to approximately 300°C. Then, the heated concrete pieces are rubbed by the media in a mill to remove the attached paste of cement from the aggregate's surface. Firstly, crushed concrete rubble up to a size

under 50 mm is placed in a vertical kerosene-fuelled furnace and heated up to 300°C. Then, the heated concrete goes to the primary rubbing equipment.

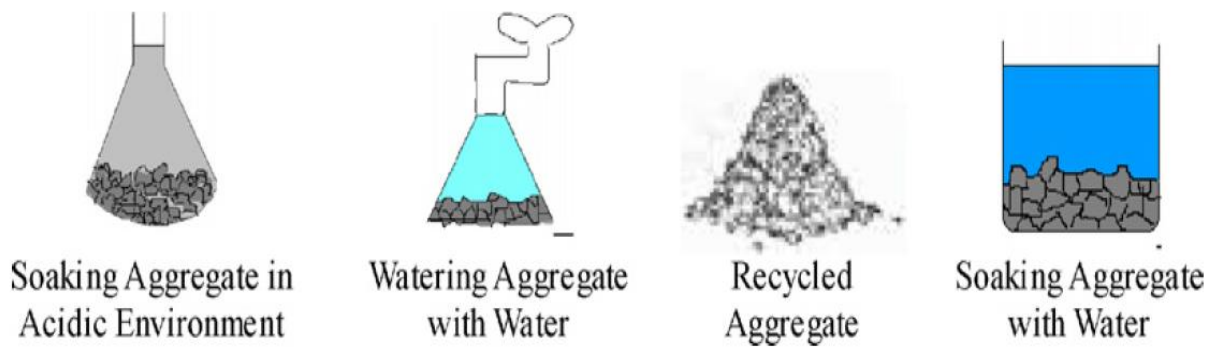
The equipment consists of a tube type mill with outer and inner cylinders. In this equipment, the concrete's heated pieces are rubbed by balls of steel as media and from the screen provided on the inner cylinder, the produced mortar is discharged to increase the rubbing treatment efficiency. Then, the removed mortar and coarse aggregate go to secondary rubbing equipment where the cement adhering to fine aggregate is eliminated by coarse aggregate as media. From the secondary equipment, all the aggregates are fed into a vibrating screen of 5 mm and separated into fine and coarse aggregate. The fine powder is swept by air that is generated in secondary equipment collected in a bag filter. The average ratios of fine powder generation and aggregate recovery to original concrete by weight are 30% of fine aggregate, 35% of coarse aggregate and 35% of fine powder, respectively (Shima *et al.*, 2005).



**Figure 1.15: Process flow of Heat & Rubbing method to produce high-quality recycled aggregate, (Shima *et al.*, 2005)**

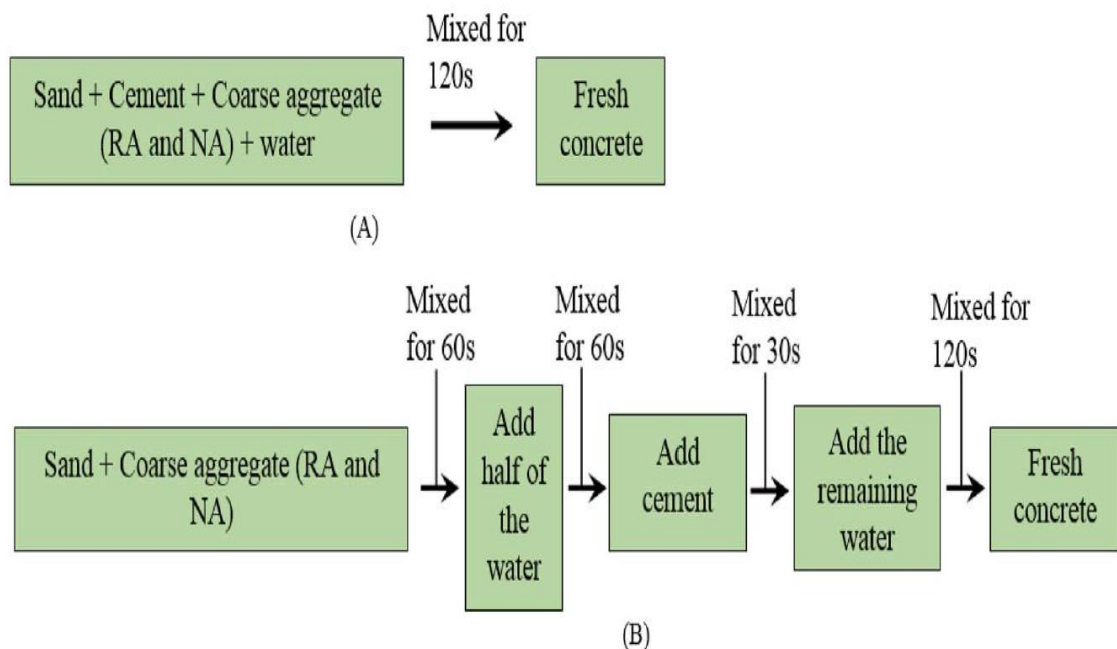
- iii. **Pre-soaking in Acid:** The cement hydration products in hardened paste can be dissolved in a solution of acid. The procedure is to soak the coarse recycled concrete aggregates (CRCA) in an acidic solution composed of Acetic acid ( $C_2H_4O_2$ ) (99.7%) and Hydrochloric acid (HCL) (37%) at a less concentration of 0.1 M at room temperature for 24 h around 20°C. To provide an appropriate acidic environment for CRCA, less concentration of the acidic solution is chosen and drained to remove the acidic solution. Then, at  $105\pm 5^\circ C$ , the

samples are dried out without affecting the RCA quality. Now, in distilled water CRCA is submerged for 24 h to prepare for performing tests. By using this method, it has been noticed that the water absorption of recycled aggregates is reduced (*Al-Bayati et al., 2016*).



**Figure 1.16: Procedure of Pre-soaking treatment used for recycled concrete aggregate, (*Al-Bayati et al., 2016*)**

- iv. **Two-Stage Mixing Approach (TSMA):** For improving the quality of the concrete which is made up of RCA, TSMA is developed. In this method, the water that is to add in concrete is divided into 2 portions and it provided to concrete mix at separate times. In this method, firstly all the aggregates (coarse and fine) are mixed for the time of 60 seconds, then, in this mix of aggregates first part of water is provided and again for a time of 60 seconds process of mixing is done.



**Figure 1.17: Sequence of mixing for the (A) Normal Mixing Approach & (B) Two-Stage Mixing Approach, (*Tam and Tam, 2007*)**

After this 60-second aggregate mixing along with the first part of water, now cement is provided in the mix and again mix them for the time of 30 seconds. Then, the second part of water is provided in the mix and again mix them for the time of 120 seconds. The ITZ of concrete made up of RCA is improved by this method. The disadvantage of this method is a long time taken for mixing than that of normal mixing approach (NMA) (*Tam and Tam, 2007*).

- v. **Self-Healing:** In the self-healing process, the recycled aggregates are immersed in the water for approximately 30 days. Unhydrated cement particles get a good chance during this time period to again react with the water for enhancing the properties of particles of concrete (*Despotovic, 2016*).
- vi. **Ultrasonic Cleaning:** In an ultrasonic (US) bath, the crushed concrete is cleaned to remove the crumbs that are observed on the untreated aggregate's surface. Firstly, in the US bath, the aggregates are immersed with a large quantity of water in it and they are treated for 10 minutes. After that this water is replaced with the clean water and again the aggregates are cleaned for 10 minutes. This activity is repeated many times until the clear water is obtained. It is noticed during the cleaning process that recycled aggregates produced from poor grade concrete require a large number of cleaning cycles until the clear water is obtained than that of high-grade concrete (*Katz, 2004*).



**Figure 1.18:** Shows the Digital Ultrasonic Cleaner Bath Equipment, (<https://m.alibaba.com/countrysearch/CN/ultrasonic-cleaner-equipment.html>)

vii. **Mineral Admixture Solution:** Some approaches like by impregnating RCA in silica fume solution or surface coating of RCA with paste of low w/c ratio or by impregnating in another solution of mineral admixture helped in healing the cracks or pores present in RCA. Impregnation of RCA in any other mineral admixtures or with a silica fume solution helps the silica fume particles to penetrate into the loose and cracked layer of aggregate. Due to silica fume's filling effect, during hardening of concrete, it helps to improve its ITZ. Furthermore, silica fume's pozzolanic reaction with  $\text{Ca}(\text{OH})_2$  to form secondary C-S-H gel which will strengthen the RCA's weak structure to form an improved zone. At an early stage, silica fume treatment has a stronger influence on filling as compared to the pozzolanic reaction which develops more slowly. Other pozzolanic substances like fly ash, GGBS etc. shows a similar effect. This improves the strength and durability performance of recycled aggregate (*Despotovic, 2016*).

## **1.9 CARBONATION METHOD USED TO IMPROVE THE QUALITY OF RECYCLED CONCRETE AGGREGATE**

### **1.9.1 Definition**

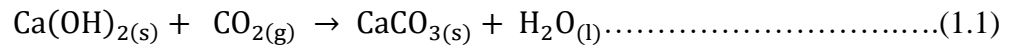
When in a solution or drink, the carbon dioxide ( $\text{CO}_2$ ) gas is dissolved under very high pressure, that process is known as "Carbonation". In soda water bottles and soft drinks, it is done to give "bite" to flavour, when you drink the carbonated drink it creates a slight burning sensation, also customers enjoy its fizzy taste. Because at lower pressure  $\text{CO}_2$  gas is less soluble when bottle opens and pressure is relieved, the gas which is previously dissolved now escapes as bubbles. 8 grams per litre is the maximum amount of carbon dioxide which can be dissolved in the water ([www.unesda.eu](http://www.unesda.eu)).

### **1.9.2 Carbonation of concrete**

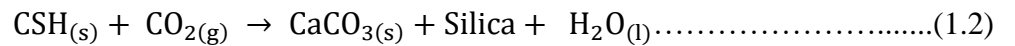
Carbon dioxide ( $\text{CO}_2$ ) present in the atmosphere approximately about 0.03% by volume. To form the various carbonate minerals, it can decompose by reacting with the cement hydration products in concrete. Carbonation of concrete is that process that advances inwards from the surface of the exposed concrete. Concrete's outer layer is known as the carbonated layer where the reaction with  $\text{CO}_2$  has been taken place. Portland cement concretes are concerned principally with this digest.  $\text{Ca}(\text{OH})_2$  and CSH gel are two hydration products of Portland cement in concrete.

The phenomenon of concrete's carbonation derived from the joining of several factors, such as type of binders used in concrete's preparation, concentration of  $\text{CO}_2$  to which the structure is subjected to, pore distribution of hardened concrete. For reactions to occur, internal moisture

conditions apply a determining factor besides the concrete's pore network. The pores of concrete should be partially saturated to give an appropriate environment for separating the CO<sub>2</sub> from atmosphere and the separation of concrete hydroxides, forming CaCO<sub>3</sub> that precipitates and changes the pH of concrete. Other things like presence of microcracks and temperature of concrete also influences the speed of phenomenon (*Werle et al., 2011*). The process of carbonation inside of concrete is that process in which CO<sub>2</sub> by means of diffusion intrudes into the capillary pore system of concrete. Carbon dioxide (CO<sub>2</sub>) and calcium hydroxide Ca(OH)<sub>2</sub> that are dissolved in pore water, reacts to produce calcium carbonate (CaCO<sub>3</sub>) that will settle down in capillary pores of concrete. In the pore water, calcium ions decrease by the formation of CaCO<sub>3</sub>. Due to this, further Ca(OH)<sub>2</sub> can dissolve and until all the Ca(OH)<sub>2</sub> is utilized, the reaction can go on continuously. The crystals of CaCO<sub>3</sub> continue their growth in the pores which leads to concrete densification. In Equation (1.1), simplified carbonation reaction is shown:



The other hydration products of cement in concrete like CSH gel also converts to CaCO<sub>3</sub>, water and a high degree of silica gel which is polymerized or a modified CSH gel having lowered Ca/Si ratio. No change in gel morphology is reported due to the decomposition of CSH as a result of carbonation because it is a pseudo-morphic reaction. For the hydrated matrix of ordinary Portland cement, there is enough amount of Ca(OH)<sub>2</sub> that is dissolved in pore solution which buffers the pH which is low, by the formation of carbonic acid. Hence, there are less effects on matrix of hydrated cement due to carbonation of CSH (*Zhan et al., 2013*). In Equation (1.2), the reaction is shown:



CO<sub>2</sub> from the air will have reacted with the surface of fresh concrete within a few hours or after some days. Slowly, the process penetrates into the concrete deeper at a rate which is proportional to square root of time. After a year, it may have reached to the depth of perhaps 1 mm for the concrete which is dense, having low permeability, made with low w/c ratio, or for concrete which is more permeable, porous and made using high w/c ratio, it can reach up to depth of 5 mm or more. From outside of concrete which is exposed to CO<sub>2</sub>, carbonation occurs. Because CO<sub>2</sub> has to diffuse from the pore system which also includes already carbonated concrete's surface zone, so carbonation happens at a decreasing rate. When the pores are filled with water in hydrated cement paste, CO<sub>2</sub> diffusion will be slow process, because diffusion of

CO<sub>2</sub> in the water is approximately 4 times slower than in air. Also, CO<sub>2</sub> do not react with hydrated cement and remains in gaseous form when insufficient water is present in pores. It means that on moisture content of concrete, rate of carbonation depends. In proportion to square root of the time, the depth of carbonation increases under steady hygrometric conditions, which is a characteristic of sorption not of diffusion, but carbonation includes interaction between pore system and CO<sub>2</sub>. Therefore, it is possible to represent carbonation depth (D) in millimetres as represented in Equation (1.3) (*Properties of concrete, A. M. Neville, 2011*):

$$D = K t^{0.5} \dots\dots\dots(1.3)$$

Where, K = coefficient of carbonation in mm/year<sup>0.5</sup> and

t = time of exposure in years

For example, if carbonation depth in 1 year is 1 mm in concrete, then it will be after 9 years about 3 mm, after 25 years about 5 mm, and after 100 years about 10 mm (*www.understanding-cement.com*). In concrete, rate of carbonation depends on factors like environmental conditions (like humidity, temperature and CO<sub>2</sub> concentration), quality of the concrete (like mix proportions, materials, compaction and curing). X-ray diffraction, chemical analysis, thermogravimetric analysis and infra-red spectroscopy are various ) laboratory techniques that could be used for determining carbonation depth. By treating the freshly broken concrete's surface by using an indicator solution of 1% phenolphthalein in the ethyl alcohol 70%, is the simple and common method for determining the depth of carbonation. The free Ca(OH)<sub>2</sub> shows pink colour, while uncoloured portion shows the carbonated part (*Properties of concrete, A. M. Neville, 2011*).

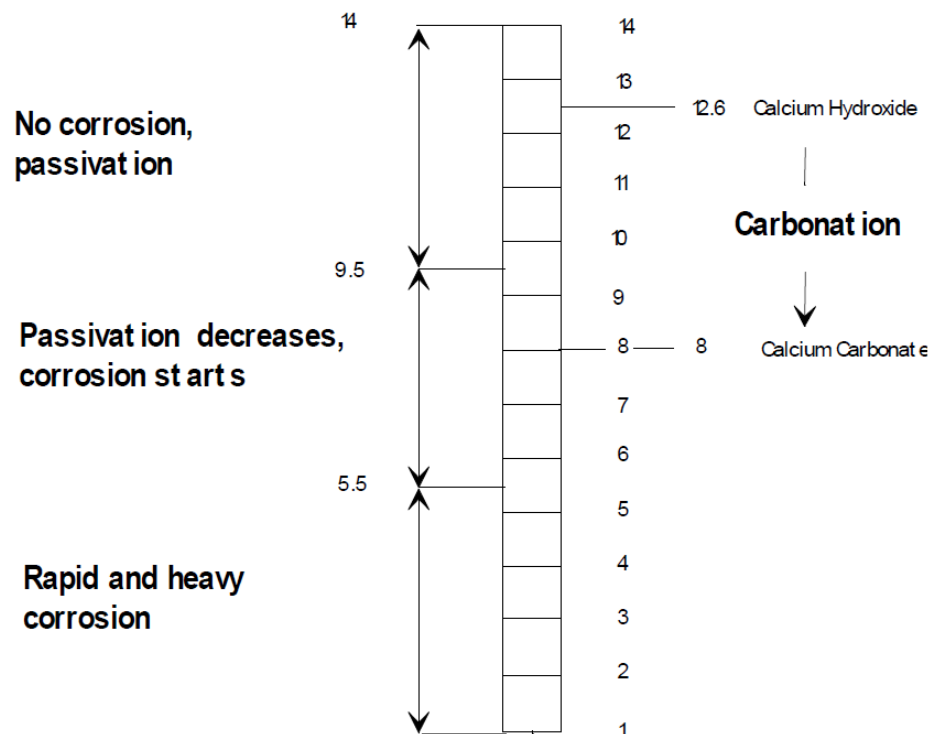
### **1.9.3 Effects of carbonation on steel and concrete**

Hydrated cement compounds are decomposed due to carbonation done by atmospheric carbon dioxide. Although, the flexural and compressive strength of concrete significantly improved by carbonation. Carbonation has a little influence on the strength of concrete, but greater influence due to reduction in permeability, however on the surfaces of concrete where for the durability, this reduced permeability could play an important role, this benefit could be cancelled by concrete undergoing carbonation by greater risk of shrinkage cracking.

In commercial, residential and public buildings, large portion of concrete is used. The concrete normally contains reinforcement, and damages can occur if the steel corrodes. Normally, in the alkaline environment within concrete, steel reinforcement corrosion is inhibited due to the presence of protective oxide film on steel surface which is chemically stable. If as a result of

carbonation, the concrete becomes less alkaline or if chloride ions in the surrounding concrete are present, then this protective oxide film can be destroyed. In reinforced concrete, the dangers of chlorides are now generally recognised and now where possible, they are avoided. It is in parking, highway, marine and coastal construction where chloride-induced damage creates a problem.

Carbon dioxide from the atmosphere diffuses into the concrete's surface pores and towards the reinforcing steel, the carbonation reaction front moves not quickly but inevitably. The surface layer of concrete which is carbonated has a decreased alkalinity (pH less than 10) as compared with the concrete which is underlying (pH more than 12.5). If the carbonation front reaches near the reinforcement and around the steel there is adequate moisture is present, then corrosion can be initiated. The corrosion products can generate internal stresses if the corrosion proceeds unchecked and can cause cracking of concrete's cover which is provided with direction of steel bars (*L. J. Parrott, 1990*). The main parameters belonging for embedded steel's corrosion risk are the depth of cover, environment, depth of carbonation, concrete's permeability to oxygen, moisture and presence of chloride. The approximate time for the starting of corrosion can be predicted if the carbonation depth is less than cover depth, assuming no changes to the degree of exposure or to the environmental conditions.

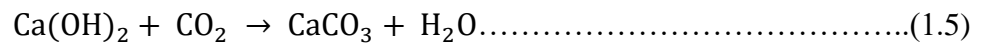


**Figure 1.19: In concrete, corrosion of steel as a function of pH, (*Technical memorandum, Gemite products inc., 2005*)**

Due to the presence of high amounts of calcium hydroxide content (lime) which is the cement hydration product, there is a high alkalinity of cement paste as shown in Equation (1.4). In Portland cement, the calcium silicate compounds (CS) are present, which when mixed with water, it reacts and produces Calcium Hydroxide (lime) and hydrated calcium silicates (CSH). Sodium (Na) and Potassium (K) which are oxides of alkali earth elements and lime forms the highly alkaline environment of new concrete.



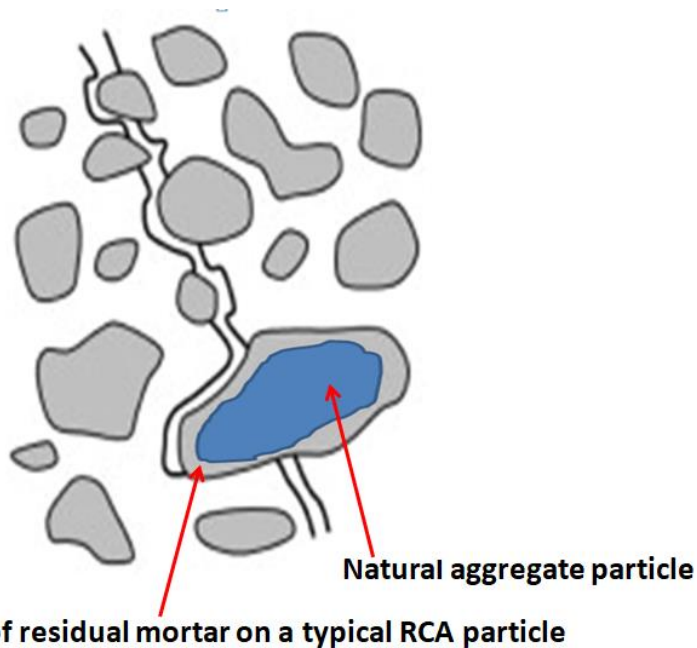
As shown in Equation (1.5), lime reacts with atmospheric CO<sub>2</sub> as the concrete ages.



Concrete "neutralizes" by this reaction and concrete's pH decreases. Steel surface's passivation protection because of alkalinity of cement paste disappears & corrosion of steel starts (*Technical memorandum, Gemite products inc., 2005*).

**1.9.4 Carbonation of recycled concrete aggregates**

Recycled Concrete Aggregate (RCA) normally consists of adhered mortar and natural coarse aggregate that is produced from Construction & Demolition waste, adhered mortar which is present makes it porous due to less dense, inhomogeneous, and high mortar content. In recycled aggregates, the volume of residual mortar normally varies from 25-60% depending on the size of aggregate.

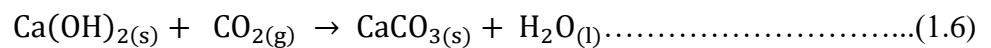


**Layer of residual mortar on a typical RCA particle**  
**Figure 1.20: Showing natural aggregate & mortar attached to it**

For aggregates of size 20-30 mm, cement paste that is attached on the surface of RA is found 20% as found by some researchers. In RCA's, various types of the interfacial transition zone (ITZ) are present between the "new" and "old" compounds, that can play an important role in the internal microstructure of concrete. Normally, the durability and mechanical properties of RCA's are weaker than those of normal concrete, mainly due to cracks formed during crushing or attached cement paste. Hence, if the adhered mortar can be improved, then it will increase the applications of RCA (*Despotovic, 2016*).

Also, it has been recently found that by using the carbonated recycled concrete aggregates (CRCA), RCA's mechanical properties can be improved, because the method of carbonation not only refine the RCA's properties, also it reduces the greenhouse effect which is originated by CO<sub>2</sub> emission. Also, this method used is lower in cost and more environment-friendly than other methods (*Li et al., 2017*).

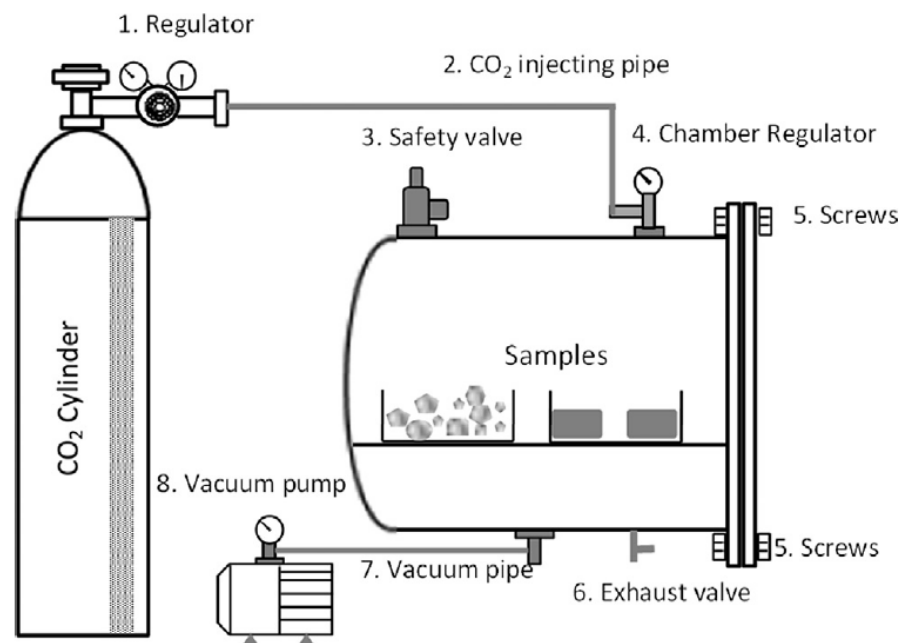
Normally, carbonation of concrete occurs with 0.03-0.06% of CO<sub>2</sub> concentration under atmospheric conditions. But, for full carbonation, it could use greater than 100 years. Alternatively, for rapidly improving the properties of RCA's, accelerated carbonation technique can be used. This method involves the reactions between cement hydration products in concrete: Ca(OH)<sub>2</sub>, C-S-H gel and CO<sub>2</sub> as shown below:



The theoretical calculation indicates that up to 50% CO<sub>2</sub> by cement mass can be used for full carbonation of concrete. CaCO<sub>3</sub> which is the reaction product precipitates in the pore space of the system, hence it will densify the whole microstructure. The previous experimental results show that carbonated RCA's causes an increase in crushing value, a decrease of water absorption and an increase in density. For example, carbonated RCA's shows 24-hour water absorption which is 1.3-2.6% lesser as compared to non-carbonated ones, affected by the strength grade of original concrete, cement content in RCA's, size of RCA's etc (*Xuan et al., 2015*).

According to the research done by the researcher (*Xuan et al., 2015*), in accelerated carbonation method, about a volume of 100 L, an airtight steel cylindrical chamber is used as shown in Figure 1.21. It was specially designed for operating the carbonation process of RCA's. Firstly, by using a vacuum pump, the chamber was vacuumed to -0.6 bars, then the CO<sub>2</sub> gas is injected

into the chamber. By using a gas regulator, the pressure of CO<sub>2</sub> in the chamber was controlled and retained at the required constant level. As per their research, RCA's were carbonated in the chamber with a concentration of CO<sub>2</sub> about 100% with a pressure level of 5 and 0.1 bars for 24 hours. To facilitate carbonation, the collected RCA's were preconditioned to an appropriate moisture content in a drying chamber and put them in for the carbonation process. The relative humidity (RH) in the drying chamber was 50±5% and the temperature was 25±3°C. By controlling the moisture content for samples near to optimal RH in between the range of 40-70%, the main reason for such pre-treatment was to increase in the rate of carbonation of concrete aggregates. As per their research, because of recycled concrete aggregates carbonation, the properties will improve like a decrease in water absorption, porosity, drying shrinkage, permeability, an increase in compressive strength, flexural strength, density.



**Figure 1.21: Schematic of carbonation chamber used to improve properties of RCA's, (Xuan et al., 2015)**

### 1.10 RESEARCH OBJECTIVES

The recycled concrete aggregates (coarse), generally have weak mechanical properties due to cracks formed during its crushing process and also contains attached cement mortar having a large number of pores which makes it less durable than natural aggregates. Therefore, the main objective of this thesis is to improve the quality of recycled concrete aggregates (coarse) by using the “Carbonation” technique and after making the concrete by using these treated aggregates, then compare the Non-destructive, Mechanical and Durability properties of the normal concrete, recycled aggregate concrete and carbonated recycled aggregate concrete.

## **1.11 ORGANISATION OF THE THESIS**

In five chapters, this thesis has been organised which are as follows:

**Chapter-1 Introduction** – It deals with the introduction, classification, applications, production process, advantages & disadvantages of using recycled concrete aggregates (RCA). It also presents the various problems regarding RCA and various techniques to improve RCA. It also presents the carbonation technique to improve the quality of RCA.

**Chapter-2 Literature Review** – It deals with recent literature on mechanical & durability properties of RCA concrete and Carbonated RCA concrete, on the basis of that the necessity of present research has been identified.

**Chapter-3 Experimental Programme** – It deals with the experimental details, properties of various materials used in research, mix design, casting details and testing setup & procedures.

**Chapter-4 Results and Discussion** – It deals with the results that are drawn from the graphs and tables for the various non-destructive, mechanical & durability properties of Normal concrete, RCA concrete and Carbonated RCA concrete and then various discussions regarding these results from experimental investigations.

**Chapter-5 Conclusions** – It deals with the various conclusions that are drawn from the experimental investigations of this study.

In the end, references that have been used in this thesis are presented.

## CHAPTER 2

### LITERATURE REVIEW

#### 2.1 GENERAL

This chapter presents a review of the literature regarding the mechanical and durability properties of Recycled aggregate concrete (RAC) and Carbonated recycled aggregate concrete (CRAC). A brief review of the previous studies done on material and structural features of RAC and CRAC is presented and in the end, the requirement of the present research work is identified.

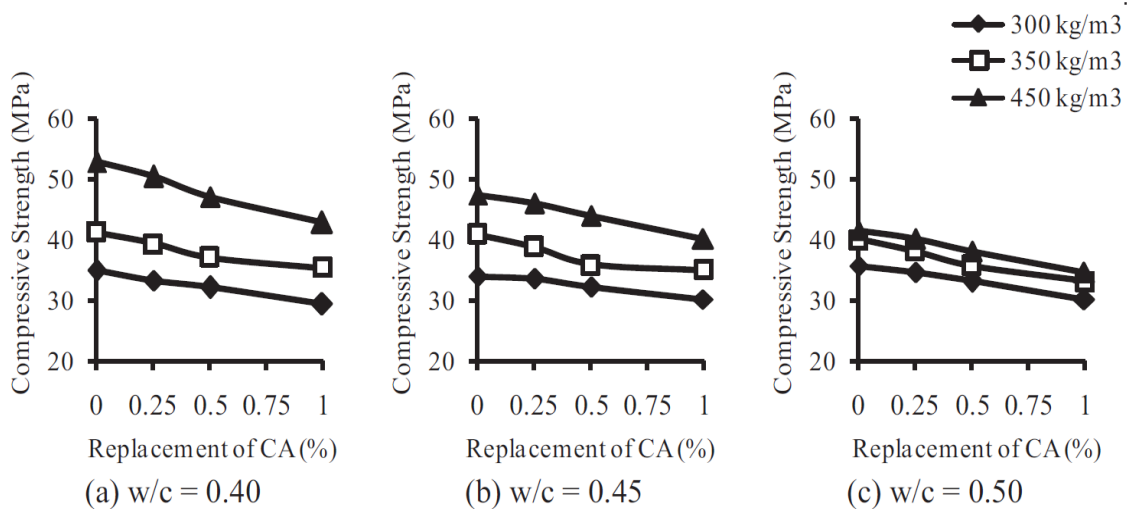
#### 2.2 RECYCLED AGGREGATE CONCRETE (RAC)

The various mechanical & durability properties of Recycled aggregate concrete (RAC) are discussed as following:

##### 2.2.1 Mechanical Properties

##### 2.2.1.1 Compressive Strength

*Thomas et al. (2018)* prepared a total 36 mixes for various cement content, w/c ratio and levels of aggregate replacement. The cement content ranges from 300 kg/m<sup>3</sup> to 450 kg/m<sup>3</sup>, w/c ratio ranges from 0.4 to 0.5 and aggregates were replaced at 0%, 25%, 50%, 100% by volume. It was observed that with an increase in RCA replacement % with natural coarse aggregates, the compressive strength of concrete mixes decreases.



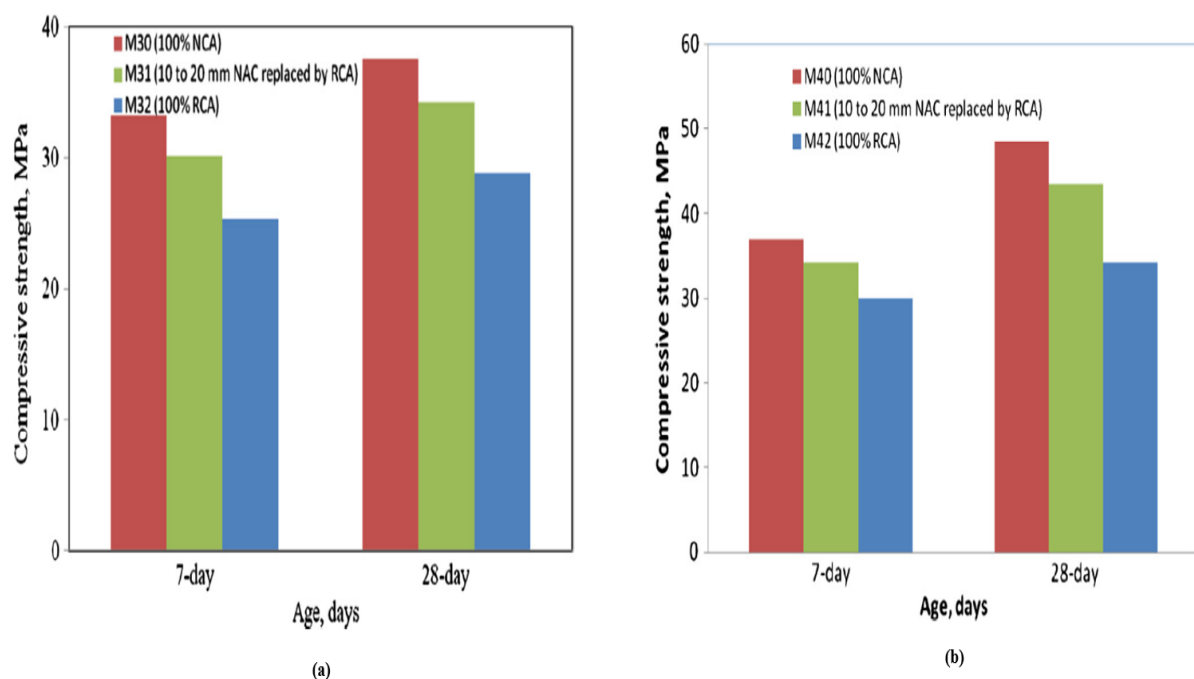
**Figure 2.1: Effect of natural aggregate replacement with RCA on the compressive strength of concrete, (*Thomas et al., 2018*)**

When 25% of RCA were replaced with natural aggregates, it shows 1.5-5% reduction in compressive strength of concrete. When 100% of RCA were replaced with natural aggregates, it shows 11-19% reduction in compressive strength of concrete. The concrete at a constant aggregate replacement level, w/c ratio and having higher cement content shows a higher compressive strength in all mixes. RCA concrete having lowest w/c ratio shows maximum compressive strength. In a mix, having 450 kg/m<sup>3</sup> of cement, 0.5 w/c ratio and 100% RCA replacement with natural aggregates, shows a maximum reduction in compressive strength (19%).

*Poon et al. (2004)* investigated the influence of hardened and fresh concrete properties, of moisture states of recycled and natural aggregates. Various concrete mixes were made by using recycled and natural aggregates with different proportions. Aggregates moisture states were controlled at saturated surface-dried (SSD), oven-dried (OD) and air-dried (AD). Between the ages of 28, 7 and 3 days, hardened concrete's compressive strength was determined. It was determined that the mixes of concrete which were made by using recycled aggregates, the highest compressive strength was shown by the air-dried (AD) aggregate concretes. The recycled aggregates which were saturated surface-dried (SSD) shows the highest negative effect on strength of concrete, due to the "bleeding" of extra water in aggregates that were pre-wetted in fresh concrete. It was observed that using the air-dried (AD) aggregates and using recycled aggregates not more than 50% should be optimum for making the normal strength recycled aggregate concrete.

*Ozbakkaloglu et al. (2017)* prepared 14 unique concrete batches, 11 for RAC and 3 for NAC. Two mixing approaches were used, Normal mixing approach (NMA) and Two-stage mixing approach (TSMA) for preparing concrete. Natural aggregates were replaced with recycled aggregates at 0%, 25%, 50%, 100%. The letters N and H used in figures represent normal strength and high strength mixes of concrete. This was followed by letters C (for coarser aggregate) and F (for finer aggregate), which were used to specify the grade of coarse aggregate used in mixes. It was observed that mix prepared by NMA has less compressive strength up to 6% than mix prepared by TSMA, due to improvement in the bond of aggregate to mortar by TSMA. It was also observed that for a given w/b ratio, as the recycled aggregate replacement ratio increases, the compressive strength for RAC decreases.

**Rakesh Kumar (2017)** prepared two series of concrete mixes, by using 0.44 (series 1) and 0.38 (series 2) water-cement ratios differently as shown in figure 2.2. M30 and M40 represent 100% natural coarse aggregates (4.75-20 mm), M31 and M41 represent natural coarse aggregates that were replaced by RCA in range of 10-20 mm, M32 and M42 represents 100% recycled coarse aggregates (4.75-20 mm) for series 1 and 2 respectively. It was observed that with an increase in RCA replacement with natural coarse aggregates, the compressive strength of concrete mixes decreases. In series 1 mixes, M31 shows 10% less and M32 shows 20% less compressive strengths than M30 mix respectively. Also, in series 2 mixes similar trends were observed. This reduction was mainly due to the presence of many cracks and micropores in the mortar attached to RCAs.



**Figure 2.2: Shows the compressive strength of (a) series 1 and (b) series 2 mixes, (Rakesh Kumar, 2017)**

**Rahal (2007)** investigated that for recycled aggregate concrete, the compressive strength was more than 80% as compared to the concrete with natural aggregates, when aggregate's relative water absorption was below 1.8%, whereas for recycled aggregate concrete, the compressive strength was dropped significantly around 40% as compared to the concrete with natural aggregates, when aggregate's relative water absorption was above 5.5%. On the surface of RA, large quantities of old cement paste were present because of insufficient hydration and formation of a weak interface-zone between the various components of the concrete matrix, which can be the reason for the poor development of concrete's compressive strength.

**Tangchirapat et al. (2008)** investigated about the concretes made by using 100% coarse recycled aggregate and sand was replaced at 0%, 50% and 100% by recycled fine aggregate along with ground rice husk-bark ash. Cement was replaced at 20%, 35% and 50% by the rice husk-bark ash. It was observed that lower compressive strength values are obtained due to the high amount of coarse and fine recycled aggregates usage in concrete. Though conventional concrete made by using 35% rice husk-bark ash showed lesser strength than concrete made by using river sand and 100% coarse recycled aggregates.

**Gonzalez and Etxeberria (2014)** analysed the properties for the high performance recycled aggregate concrete. In this research, recycled aggregates were produced by crushing high strength concrete (40, 60 and 100 MPa) and replaced with natural aggregates at 20%, 50% and 100%. The compressive strength was greater as compared to the control mixture when recycled aggregates (from 100 MPa) were used to make a concrete mix. Cement paste of high quality was capable to make a good bond with recycled aggregates. Only, recycled aggregates (from 40 MPa) when replaced at 100% performed poorly. The negative influence was shown due to inferior attached mortar present on the aggregates. In recycled aggregate concrete, to compensate for this, usage of low w/c ratio of 0.285 was done.

**Surya et al. (2013)** studied the concrete mixes of 5 different types without and with class F Fly ash. Three mixes made by using recycled aggregates at replacement levels of 100%, 75% and 50% with the natural aggregates were prepared by using fly ash. Also, two concrete mixes made by using natural aggregates without and with fly ash. Waste dump of lab samples was crushed to generate recycled aggregates. Constant w/c ratio of 0.4 was used. As compared to normal concrete, recycled aggregate concrete shows better compressive strength. Maximum compressive strength was shown by 100% recycled aggregate concrete. Due to the addition of fly ash, recycled aggregate concrete's transition zone was improved making its strength greater or parallel than normal concrete.

**Dallas et al. 2014** investigated the compressive strength of recycled aggregate concrete by using silica fume. In this study, recycled aggregates (from concrete, tiles and bricks) of 2 types were used. Aggregates were replaced at 30% and 40%, later simultaneously both types were used for replacement of 70%. By weight of cement, silica fume was replaced at 5% and 10%. The effect of silica fume was reduced by the impurities in recycled aggregates as shown in results. Also, as compared to normal concrete, the concrete with recycled aggregates and using silica fume of 5% and 10% shows good results.

**Table 2.1: Compressive strength at 28 days, (Dilbas et al., 2014)**

Notation	SF (%)	RA (%)	Compressive strength (MPa)
1st Group			
NAC	0	0	35.8
RA1C	0	40	33.0
RA2C	0	30	34.1
RA12C	0	70	29.1
2nd Group			
NACSF5	5	0	39.9
RA1CSF5	5	40	34.8
RA2CSF5	5	30	35.2
RA12CSF5	5	70	33.2
3rd Group			
NACSF10	10	0	45.5
RA1CSF10	10	40	37.2
RA2CSF10	10	30	38.5
RA12CSF10	10	70	28.9

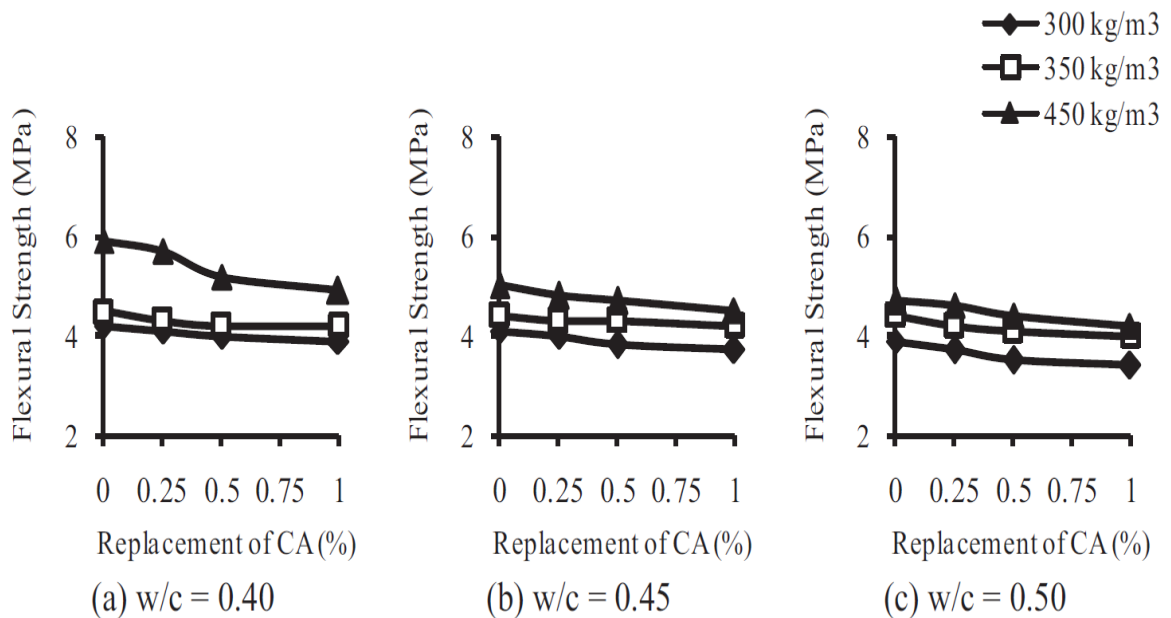
*Kou et al. (2012)* used commercial recycled aggregates and replaced them with natural aggregates at 100%, 50%, 25% and 0% in concrete mixes. A reduction of 12.2% in compressive strength at 28 days was observed for the 100% recycled aggregate concrete as compared to the natural aggregate concrete. An increase in compressive strength at 90 days was observed for the 20% recycled aggregate concrete as compared to the natural aggregate concrete.

**Table 2.2: Compressive strength of concrete at 28 and 90 days, (Kou et al., 2012)**

Concrete mixes	Recycled aggregate (%)	Compressive strength (MPa)	
		28-day	90-day
RA0	0	43.4	47.8
RA20	20	45.3	49.1
RA50	50	42.5	47.5
RA100	100	38.1	45.5

### 2.2.1.2 Flexural Strength

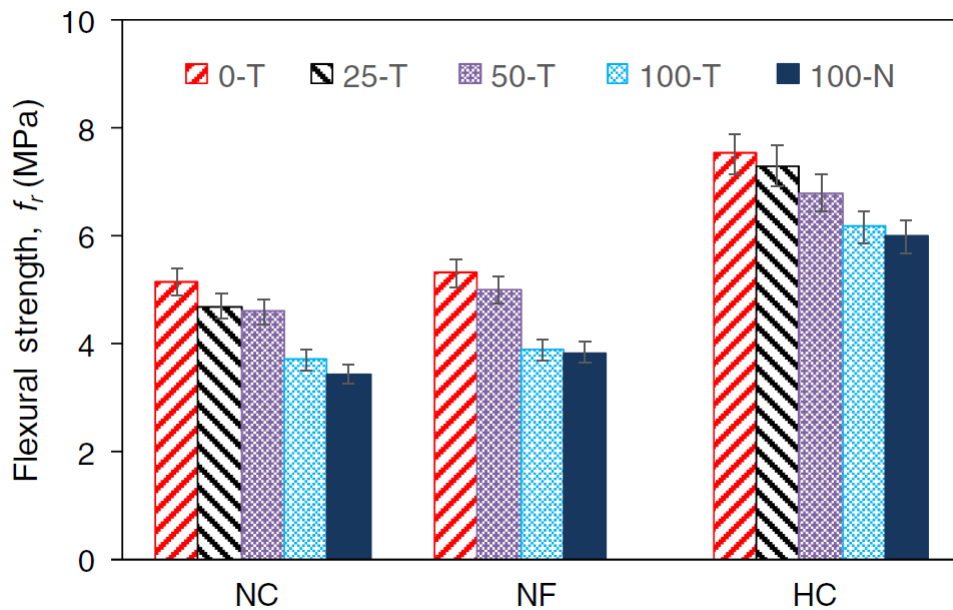
*Thomas et al. (2018)* prepared a total 36 mixes for various cement content, w/c ratio and levels of aggregate replacement. The cement content ranges from 300 kg/m<sup>3</sup> to 450 kg/m<sup>3</sup>, w/c ratio ranges from 0.4 to 0.5 and aggregates were replaced at 0%, 25%, 50%, 100% by volume. It was observed that with an increase in RCA replacement % with natural coarse aggregates, the flexural strength of concrete mixes decreases. When 25% of RCA were replaced with natural aggregates, it shows 2-5% reduction in flexural strength of concrete. When 100% of RCA were replaced with natural aggregates, it shows 7-17% reduction in flexural strength of concrete. In a mix, having 450 kg/m<sup>3</sup> of cement, 0.5 w/c ratio and 100% RCA replacement with natural aggregates, shows a maximum reduction in flexural strength (13%). With the increase in w/c ratio, the flexural strength decreases and increases when the cement content of mix increases.



**Figure 2.3: Effect of natural aggregate replacement with RCA on the flexural strength of concrete, (*Thomas et al., 2018*)**

*Ozbakkaloglu et al. (2017)* prepared 14 unique concrete batches, 11 for RAC and 3 for NAC. Two mixing approaches were used, Normal mixing approach (NMA) and Two-stage mixing approach (TSMA) for preparing concrete. Natural aggregates were replaced with recycled aggregates at 0%, 25%, 50%, 100%. The letters N and H used in figures represent normal strength and high strength mixes of concrete. This was followed by letters C (for coarser aggregate) and F (for finer aggregate), which were used to specify the grade of coarse aggregate used in mixes. From the figure 2.4, it can be seen that flexural strength for all mixes decreases with an increase in the RCA% due to a decrease in aggregate-mortar ITZs strength with

increasing RCA% in concrete. Also, the flexural strength of concrete prepared by TSMA were higher up to 9% than the concrete prepared by NMA, due to improvement in the bond of aggregate to mortar by TSMA.



**Figure 2.4: Concrete's flexural strength at 28 days, (Ozbakkaloglu et al., 2017)**

*Surya et al. (2013)* studied the concrete mixes of 5 different types without and with class F Fly ash. Three mixes made by using recycled aggregates at replacement levels of 100%, 75% and 50% with the natural aggregates were prepared by using fly ash. Also, two concrete mixes made by using natural aggregates without and with fly ash. Waste dump of lab samples was crushed to generate recycled aggregates. Constant w/c ratio of 0.4 was used. As compared to normal concrete, recycled aggregate concrete shows better flexural strength. Maximum flexural strength was shown by the 100% recycled aggregate concrete. Due to the addition of fly ash, recycled aggregate concrete's transition zone was improved making its strength greater or parallel than normal concrete.

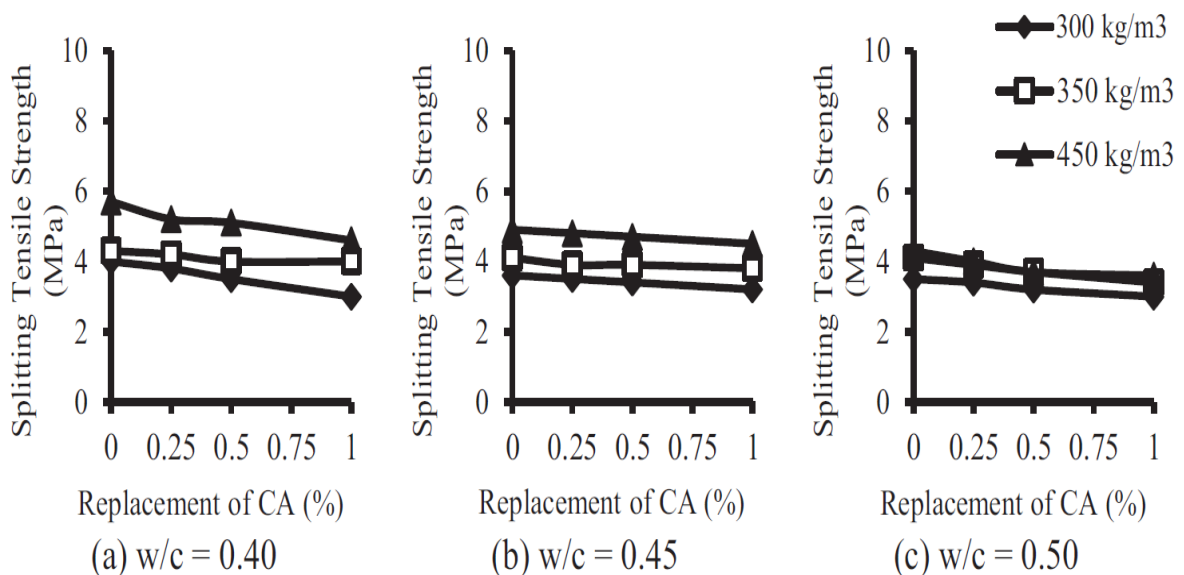
*Rakesh Kumar (2017)* prepared two series of concrete mixes, by using 0.44 (series 1) and 0.38 (series 2) water-cement ratios differently. M30 and M40 represent 100% natural coarse aggregates (4.75-20 mm), M31 and M41 represent natural coarse aggregates that were replaced by RCA in range of 10-20 mm, M32 and M42 represents 100% recycled coarse aggregates (4.75-20 mm) for series 1 and 2 respectively. It was observed that with an increase in RCA replacement with natural coarse aggregates, the flexural strength of concrete mixes decreases as shown in Table 2.3. In series 1 mixes, M31 shows insignificant reduction and M32 shows 20% reduction in flexural strength than M30 mix respectively. Also, in series 2 mixes similar trends were observed.

**Table 2.3: Flexural strength of concrete mixes, (Rakesh Kumar, 2017)**

Flexural strength, MPa	Concrete mix series 1			Concrete mix series 2		
	M30 (100% NCA)	M31 (10 to 20 mm NCA replaced by RCA)	M32 (100% RCA)	M40 (100% NCA)	M41 (10 to 20 mm NCA replaced by RCA)	M42 (100% RCA)
7-day	4.2	4.0	3.6	5.3	4.9	4.6
28-day	5.0	4.6	3.9	6.1	5.8	5.1

**2.2.1.3 Split Tensile Strength**

Thomas et al. (2018) prepared a total 36 mixes for various cement content, w/c ratio and levels of aggregate replacement. The cement content ranges from 300 kg/m<sup>3</sup> to 450 kg/m<sup>3</sup>, w/c ratio ranges from 0.4 to 0.5 and aggregates were replaced at 0%, 25%, 50%, 100% by volume. It was observed that with an increase in RCA replacement % with natural coarse aggregates, the splitting tensile strength of concrete mixes decreases. When 25% of RCA were replaced with natural aggregates, it shows 2-8% reduction in splitting tensile strength of concrete.

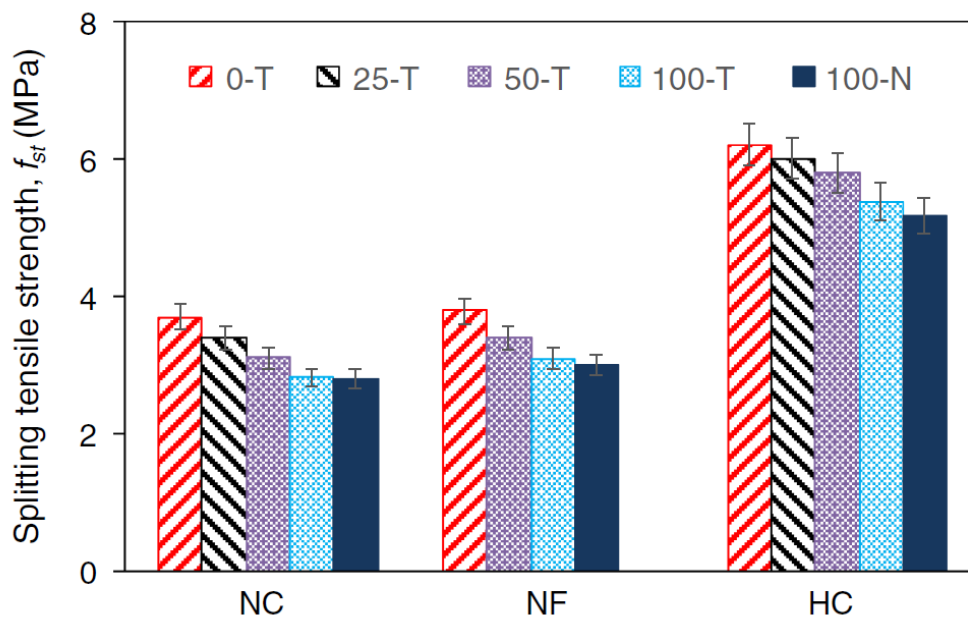


**Figure 2.5: Effect of natural aggregate replacement with RCA on splitting tensile strength of concrete, (Thomas et al., 2018)**

When 100% of RCA were replaced with natural aggregates, it shows 7-19% reduction in splitting tensile strength of concrete. In a mix, having 450 kg/m<sup>3</sup> of cement, 0.5 w/c ratio and

100% RCA replacement with natural aggregates, shows a maximum reduction in splitting tensile strength (28%). With the increase in w/c ratio, the splitting tensile strength decreases and increases when the cement content of mix increases

*Ozbakkaloglu et al. (2017)* prepared 14 unique concrete batches, 11 for RAC and 3 for NAC. Two mixing approaches were used, Normal mixing approach (NMA) and Two-stage mixing approach (TSMA) for preparing concrete. Natural aggregates were replaced with recycled aggregates at 0%, 25%, 50%, 100%. The letters N and H used in figures represent normal strength and high strength mixes of concrete. This was followed by letters C (for coarser aggregate) and F (for finer aggregate), which were used to specify the grade of coarse aggregate used in mixes. From the figure 2.6, it can be seen that split tensile strength for all mixes decreases with an increase in the RCA% due to a decrease in aggregate-mortar ITZs strength with increasing RCA% in concrete. Also, split tensile strength of concrete prepared by TSMA were higher up to 3% than the concrete prepared by NMA, due to improvement in the bond of aggregate to mortar by TSMA.



**Figure 2.6: Concrete's splitting tensile strength at 28 days, (*Ozbakkaloglu et al., 2017*)**

*Tangchirapat et al. (2008)* investigated about the concretes made by using 100% coarse recycled aggregate and sand was replaced at 0%, 50% and 100% by recycled fine aggregate along with ground rice husk-bark ash. Cement was replaced at 20%, 35% and 50% by the rice husk-bark ash. Concrete's splitting tensile strength was represented as the percentage of its compressive strength. The results indicated that recycled aggregate concrete's splitting tensile strength was not much different as compared to the concrete made by using natural aggregates.

Rice husk-bark ash's addition did not affect the splitting tensile strength's characteristics of recycled aggregate concrete.

**Gonzalez and Etxeberria (2014)** analysed the properties for the high performance recycled aggregate concrete. In this research, recycled aggregates were produced by crushing high strength concrete (40, 60 and 100 MPa) and replaced with natural aggregates at 20%, 50% and 100%. A good performance was shown by all concrete mixtures, except the concrete prepared by using 100% of 40 MPa RCA. The tensile strength of greater than 4.5 MPa was achieved by all other series. The splitting tensile strength was not appearing to be very influenced regarding the various replacement level of RAC in each quality of recycled aggregate used.

**Surya et al. (2013)** studied the concrete mixes of 5 different types without and with class F Fly ash. Three mixes made by using recycled aggregates at replacement levels of 100%, 75% and 50% with the natural aggregates were prepared by using fly ash. Also, two concrete mixes made by using natural aggregates without and with fly ash. Waste dump of lab samples was crushed to generate recycled aggregates. Constant w/c ratio of 0.4 was used. As compared to normal concrete, recycled aggregate concrete shows better splitting tensile strength. Maximum splitting tensile strength was shown by the 100% recycled aggregate concrete. Due to the addition of fly ash, recycled aggregate concrete's transition zone was improved making its strength greater or parallel than normal concrete.

**Kou et al. (2012)** used commercial recycled aggregates and replaced them with natural aggregates at 100%, 50%, 25% and 0% in concrete mixes. At 28 days, as compared to control mixture, splitting tensile strength values was lower for recycled aggregate concrete mixes. At 90 days, as compared to a control mixture, for recycled aggregate concrete mixes the gain % was higher. This was because of the ITZ's microstructure and improved bond strength between aggregates and new cement paste.

**Dilbas et al. 2014** investigated the compressive strength of recycled aggregate concrete by using silica fume. In this study, recycled aggregates (from concrete, tiles and bricks) of 2 types were used. Aggregates were replaced at 30% and 40%, later simultaneously both types were used for replacement of 70%. By weight of cement, silica fume was replaced at 5% and 10%. It was observed that as compared to control mixture, the tensile strength of concrete made by using recycled aggregates of the low grade was slightly lower. Also, as compared to traditional concrete, the tensile strength of mixture having coarse recycled aggregates of better quality with and without silica fume, was greater. This shows that on splitting tensile strength, the

usage of silica fume in concrete mixtures has a very marginal increasing effect. When recycled aggregates of both qualities were used simultaneously, a severe decrease was noted.

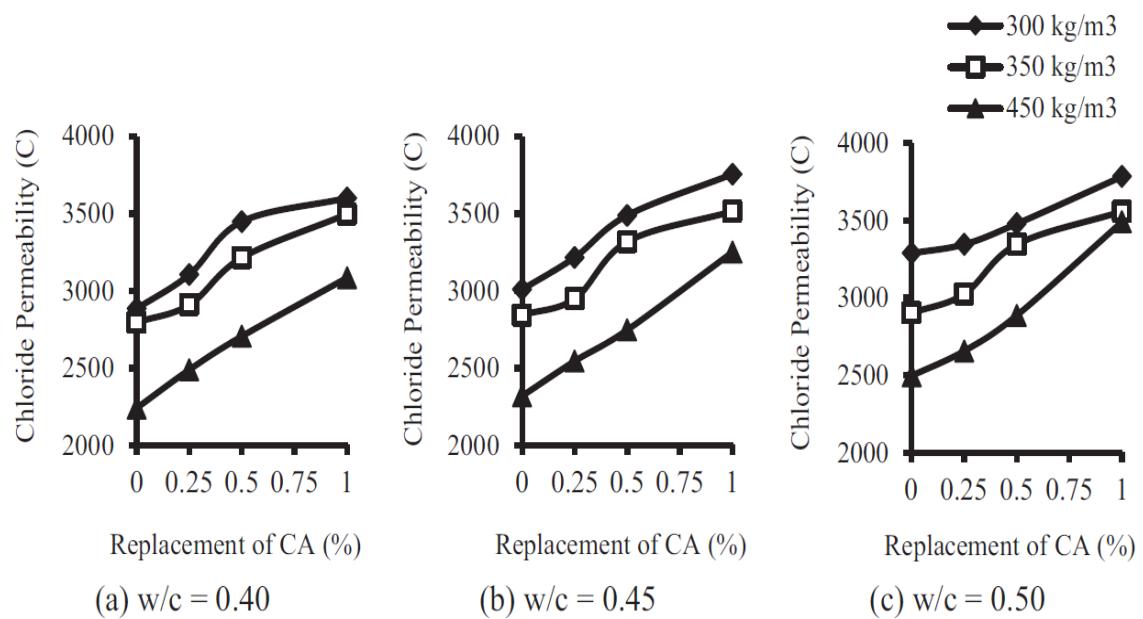
**Table 2.4: Splitting tensile strength at 28 days, (Dilbas et al., 2014)**

Notation	SF (%)	RA (%)	Compressive strength (MPa)
1st Group			
NAC	0	0	2.25
RA1C	0	40	2.24
RA2C	0	30	2.41
RA12C	0	70	1.58
2nd Group			
NACSF5	5	0	2.62
RA1CSF5	5	40	2.52
RA2CSF5	5	30	2.97
RA12CSF5	5	70	1.92
3rd Group			
NACSF10	10	0	3.40
RA1CSF10	10	40	2.46
RA2CSF10	10	30	2.63
RA12CSF10	10	70	1.62

## 2.2.2 Durability Properties

### 2.2.2.1 Rapid Chloride Permeability

*Thomas et al. (2018)* prepared a total 36 mixes for various cement content, w/c ratio and levels of aggregate replacement. The cement content ranges from 300 kg/m<sup>3</sup> to 450 kg/m<sup>3</sup>, w/c ratio ranges from 0.4 to 0.5 and aggregates were replaced at 0%, 25%, 50%, 100% by volume. It was observed that with an increase in RCA replacement % with natural coarse aggregates, the chloride penetration resistance of concrete mixes decreases. When 25% of RCA were replaced with natural aggregates, it shows 2-11% increase in chloride permeability of concrete. When 100% of RCA were replaced with natural aggregates, it shows a 15-40% increase in chloride permeability of concrete. For a w/c ratio of 0.4, 16-24% increase in chloride permeability was observed when RCA % in the mix was extended from 25% to 100%.



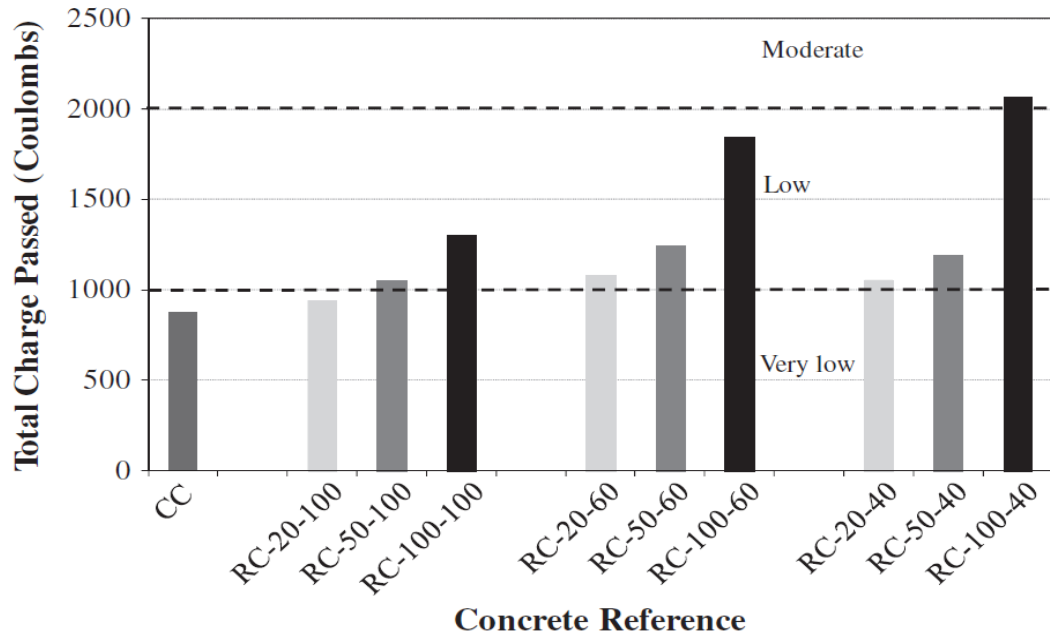
**Figure 2.7: Effect of natural aggregate replacement with RCA on chloride permeability of concrete, (Thomas et al., 2018)**

*Kou et al. (2012)* used commercial recycled aggregates and replaced them with natural aggregates at 100%, 50%, 25% and 0% in concrete mixes. It was observed that when in concrete recycled aggregates were incorporated, a reduction was shown in the chloride-ion penetration resistance. Also, better chloride-ion penetration resistance was observed when the better quality of recycled aggregates was used in concrete mixes.

*Lima et al. (2013)* studied the chloride-ion penetration resistance for the concretes made by using fly ash and recycled aggregates. Recycled aggregates were replaced at 100%, 60% and 30%. In concrete mixtures, both fine and coarse recycled aggregates were used. An extra amount of water calculated from recycled aggregate's water absorption capacity was added in various mixes to keep the water available constant for the chemical reaction. The content of fly ash was taken as "High", "Medium" and "Low". The chloride-ion penetration resistance was reduced by using recycled aggregates. The anti-chloride performance of concrete was improved by the addition of fly ash.

*Gonzalez and Etxeberria (2014)* analysed the properties for the high performance recycled aggregate concrete. In this research, recycled aggregates were produced by crushing high strength concrete (40, 60 and 100 MPa) and replaced with natural aggregates at 20%, 50% and 100%. In the concrete, as the increase in recycled aggregates content, a decrease in resistance to chloride-ion penetration was found. Results of very small corrosion range were obtained when the concrete was made by using coarse RCA of 20% and 50% replacement. The moderate

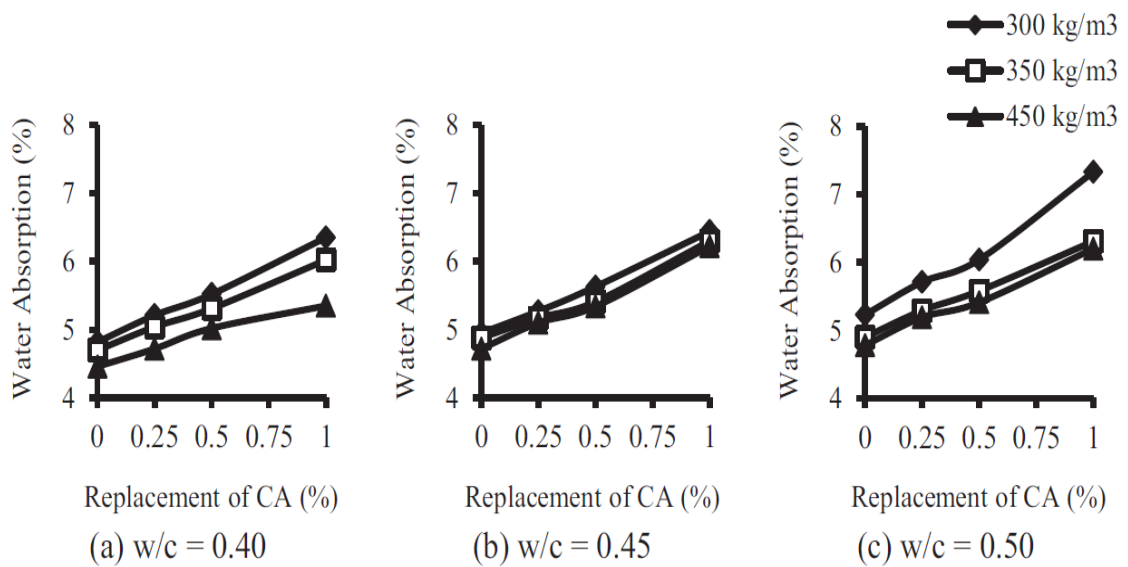
or above corrosion limit values were obtained by the total replacement of series 40 MPa and 60 MPa.



**Figure 2.8: Chloride-ion penetration of various concrete mixtures, (Gonzalez and Etxeberria, 2014)**

### 2.2.2.2 Water Absorption

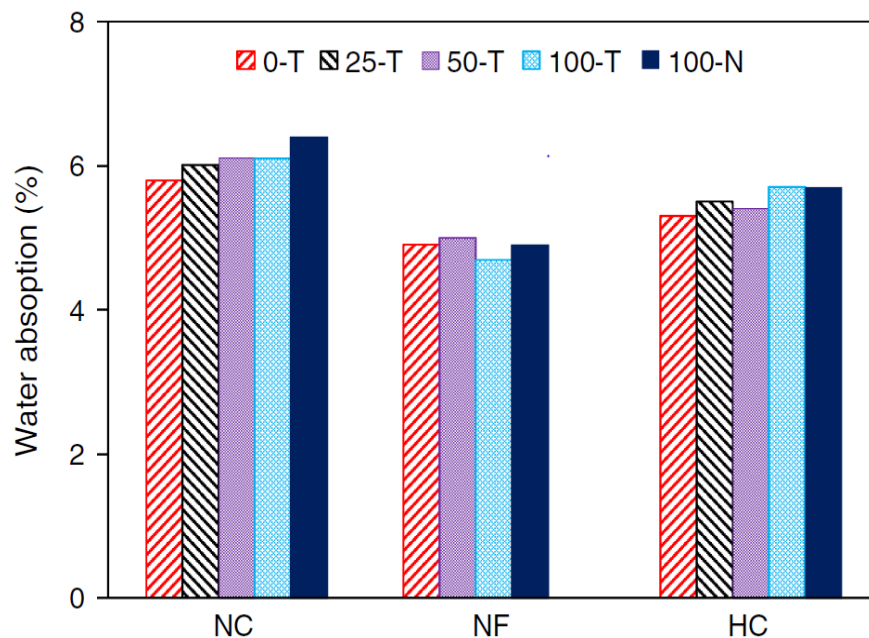
Thomas *et al.* (2018) prepared total 36 mixes for various cement content, w/c ratio and levels of aggregate replacement. The cement content ranges from  $300 \text{ kg/m}^3$  to  $450 \text{ kg/m}^3$ , w/c ratio ranges from 0.4 to 0.5 and aggregates were replaced at 0%, 25%, 50%, 100% by volume.



**Figure 2.9: Effect of natural aggregate replacement with RCA on water absorption of concrete, (Thomas *et al.*, 2018)**

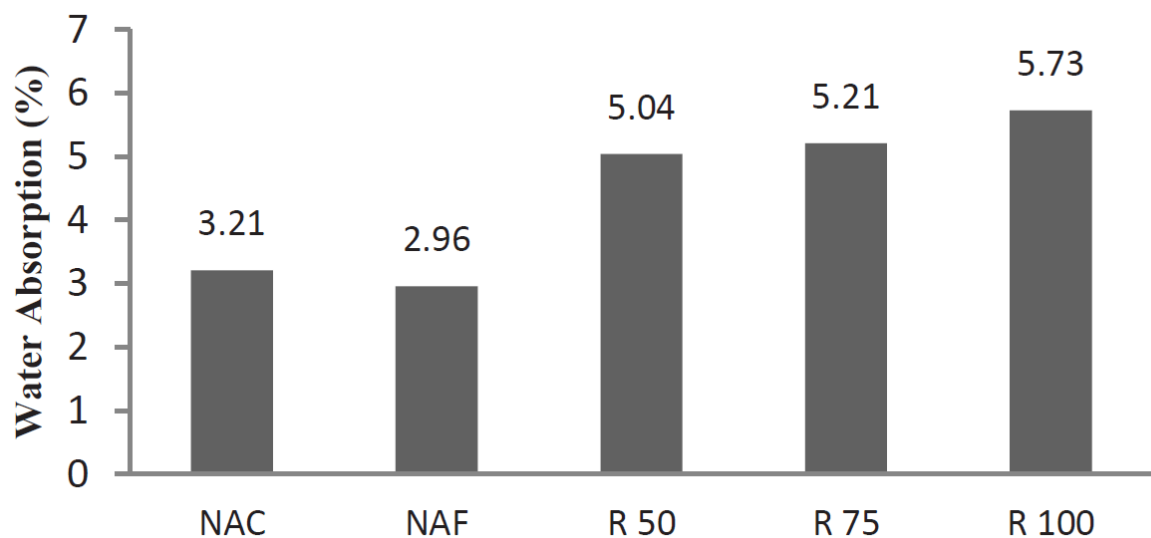
It was observed that with an increase in RCA replacement % with natural coarse aggregates, the water absorption of concrete mixes increases. When 25% of RCA were replaced with natural aggregates, it shows a 5-10% increase in water absorption of concrete. When 100% of RCA were replaced with natural aggregates, it shows a maximum 40% increase in water absorption of concrete for the mix having 450 kg/m<sup>3</sup> of cement and 0.5 w/c ratio. For a w/c ratio of 0.4, 13-19% increase in water absorption was observed when RCA % in the mix was extended from 25% to 100%.

*Ozbakkaloglu et al. (2017)* prepared 14 unique concrete batches, 11 for RAC and 3 for NAC. Two mixing approaches were used, Normal mixing approach (NMA) and Two-stage mixing approach (TSMA) for preparing concrete. Natural aggregates were replaced with recycled aggregates at 0%, 25%, 50%, 100%. The letters N and H used in figures represent normal strength and high strength mixes of concrete. This was followed by letters C (for coarser aggregate) and F (for finer aggregate), which were used to specify the grade of coarse aggregate used in mixes. From the figure 2.10, it can be seen that with an increase in RCA%, the water absorption in HC and NC series mixes increases because recycled aggregates absorb high amounts of water than natural aggregates. The water absorption of NC series mixes was more up to 30% at 28 days than the NF series mixes, because coarser recycled aggregates absorb more water than finer. Also, TSMA reduces the water absorption of mixes up to 5%.



**Figure 2.10: Hardened concrete's water absorption at 28 days, (*Ozbakkaloglu et al., 2017*)**

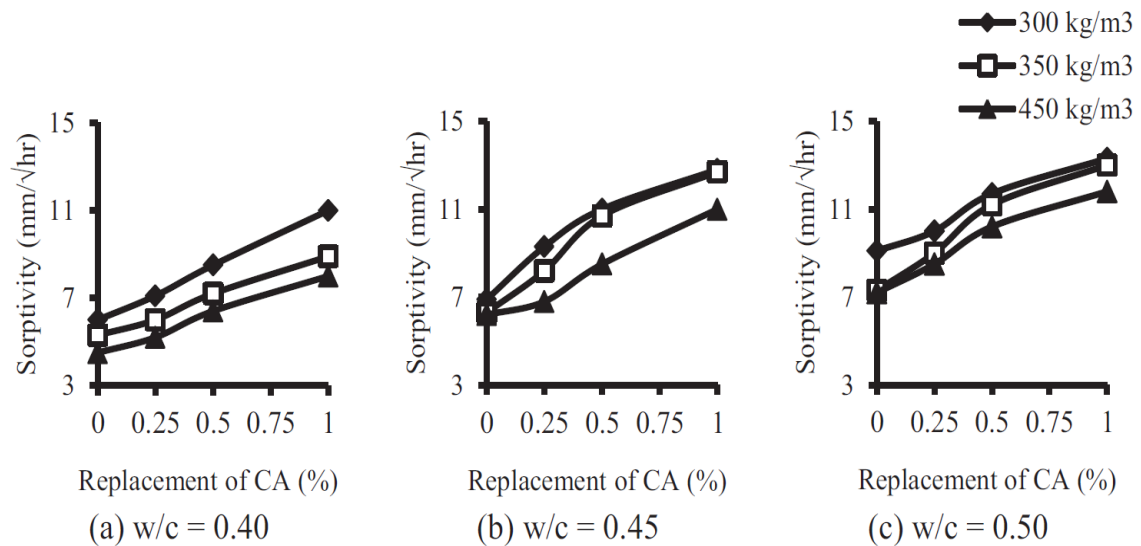
*Surya et al. (2013)* studied the concrete mixes of 5 different types without and with class F Fly ash. Three mixes made by using recycled aggregates at replacement levels of 100%, 75% and 50% with the natural aggregates were prepared by using fly ash. Also, two concrete mixes made by using natural aggregates without and with fly ash. Waste dump of lab samples were crushed to generate recycled aggregates. Constant w/c ratio of 0.4 was used. It was observed that as the proportion of recycled aggregates increases, water absorption of concrete also increases. As compared to NAC, the water absorption increased by 78.5%, 62.3% and 57% for R100, R75 and R50 mixes respectively and the same increased by 93.6%, 76% and 70.3% as compared to the NAF. In this case, as compared to NA, the water absorption of RCA was approximately 6.5 times higher.



**Figure 2.11: Water absorption variation at the different percentage of recycled aggregates, (*Surya et al., 2013*)**

### 2.2.2.3 Sorptivity

*Thomas et al. (2018)* prepared total 36 mixes for various cement content, w/c ratio and levels of aggregate replacement. The cement content ranges from 300 kg/m<sup>3</sup> to 450 kg/m<sup>3</sup>, w/c ratio ranges from 0.4 to 0.5 and aggregates were replaced at 0%, 25%, 50%, 100% by volume. It was observed that with an increase in RCA replacement % with natural coarse aggregates, the capillary absorption of concrete mixes increases. When 25% of RCA were replaced with natural aggregates, it shows 9-35% increase in sorptivity of concrete. For a w/c ratio of 0.4, an average 52% increase in sorptivity was observed when RCA % in the mix was extended from 25% to 100%.



**Figure 2.12: Effect of natural aggregate replacement with RCA on sorptivity of concrete, (Thomas et al., 2018)**

*Gonzalez and Etxeberria (2014)* analysed the properties for the high performance recycled aggregate concrete. In this research, recycled aggregates were produced by crushing high strength concrete (40, 60 and 100 MPa) and replaced with natural aggregates at 20%, 50% and 100%. It was observed that capillary water absorption for all concretes made by using the recycled aggregates was not higher as compared to the natural aggregate concrete. It was observed that in first 30 minutes, the water amount's increase (by weight) in the specimens was lower than 0.05% concerning the specimens dry weight, due to very low w/c ratio used for all concretes. With respect to its initial weight, an increase of 0.11% was found in weights of all samples after 48 h.

### 2.3 CARBONATED RECYCLED AGGREGATE CONCRETE (CRAC)

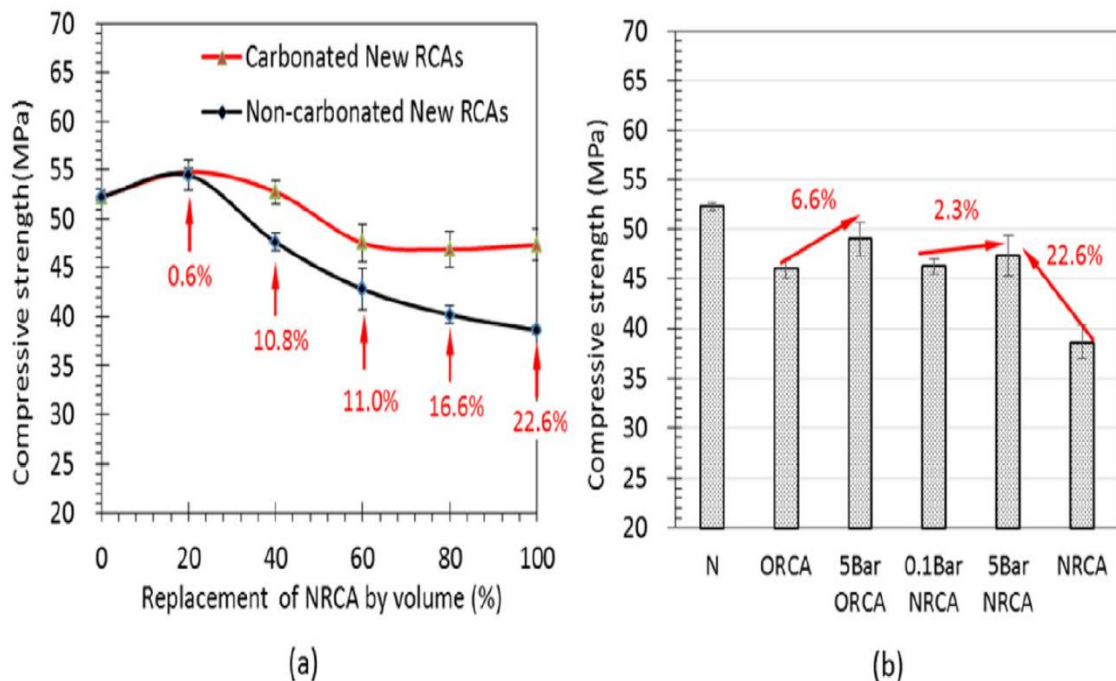
The various mechanical & durability properties of Carbonated recycled aggregate concrete (CRAC) are discussed as following:

#### 2.3.1 Mechanical Properties

##### 2.3.1.1 Compressive Strength

*Xuan et al. (2015)* studied the compressive strength behaviour of various concrete mixes at 28 days, that were prepared by using various types of coarse aggregates named natural (N), non-carbonated old type of RCA (ORCA), non-carbonated new type of RCA (NRCA), carbonated ORCA at 5 bar pressure level, carbonated NRCA at 0.1 bar pressure level and carbonated

NRCA at 5 bar pressure level, using w/c ratio of 0.55, superplasticizer to maintain slump in 150-200 mm range, also natural coarse aggregates in concrete were replaced at 0%, 20%, 40%, 60%, 80% and 100% as shown in figure 2.13. A reduction of 26.3% in the compressive strength was observed for concrete made by using 100% non-carbonated NRCA as compared to 100% natural aggregate concrete, but no noticeable reduction was found in compressive strength for replacement % up to 30%. An increase of 22.6% in the compressive strength was observed for concrete made by using 100% carbonated NRCA at 5 bar pressure level as compared to the concrete made by using 100% non-carbonated NRCA. When the natural aggregates were replaced with carbonated NRCA up to 60%, an insignificant reduction was observed in the compressive strength as compared to control concrete. Therefore, it was found that by treating RCAs with carbonation, the compressive strength of RAC increases and RCAs at higher % can also be used in concrete. The increase of 2.3% in compressive strength was found when carbonation pressure level was increased for NRCA from 0.1 to 5 bars. A slight increase of 6.6% in the compressive strength was observed for concrete made by using carbonated ORCA at 5 bar pressure level because ORCA during demolition and stages of storage had been naturally carbonated.

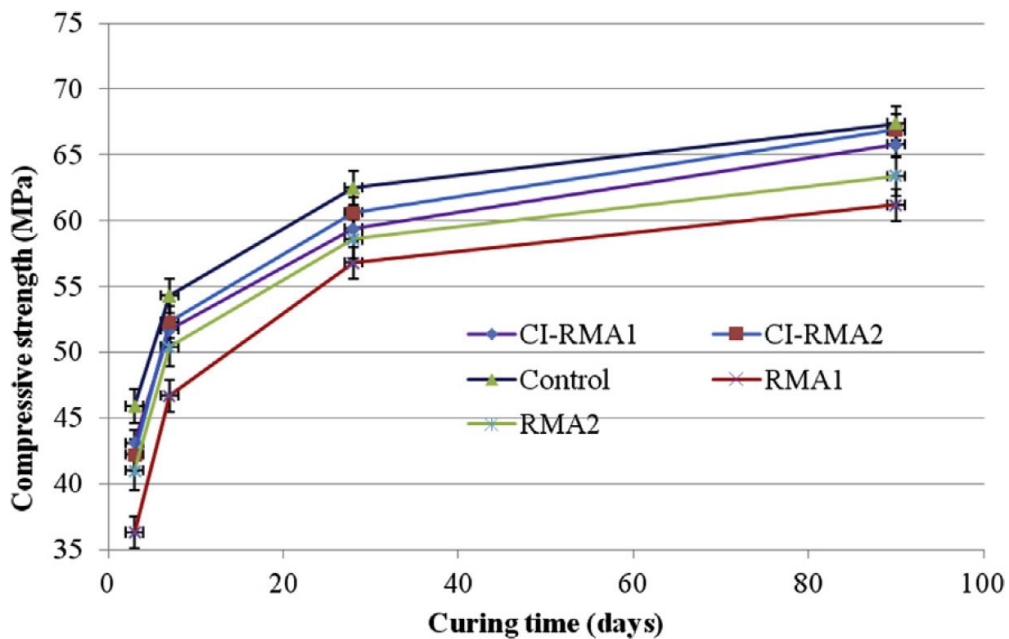


**Figure 2.13: Compressive strength of concrete prepared by using carbonated and non-carbonated RCAs at 28 days, (Xuan et al., 2015)**

*Shi-Cong et al. (2013)* studied the compressive strength behaviour of various types of concrete mixes named control (normal concrete), RMA1 (concrete containing recycled mortar aggregates of type-1), RMA2 (concrete containing recycled mortar aggregates of type-2), CI-RMA1 (concrete containing CO<sub>2</sub> improved recycled mortar aggregates of type-1), CI-RMA2 (concrete containing CO<sub>2</sub> improved recycled mortar aggregates of type-2), prepared by using w/c ratio of 0.5 for the age of 3, 7, 28 and 90 days as shown in table 2.5 and figure 2.14. It was observed that the compressive strength at 28 days for concrete mixes named CI-RMA1, CI-RMA2, RMA1 and RMA2 was 3%, 1%, 10% and 8% less as compared to control concrete. Also, as compared to control concrete, the compressive strength of CI-RMA2 concrete mix was only 1% less at 90 days. Therefore, it was observed that CO<sub>2</sub> curing regime enhanced the mechanical properties of recycled aggregates.

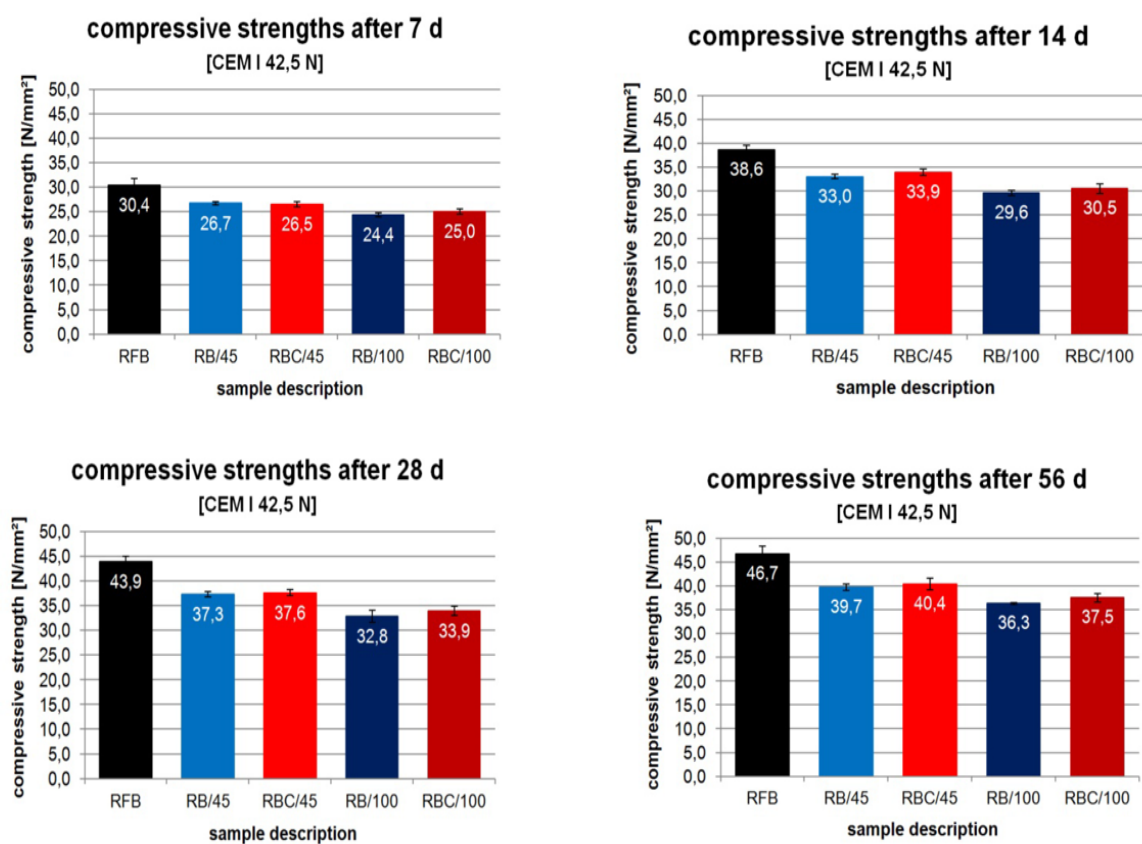
**Table 2.5: Relative concrete's compressive strength, (*Shi-Cong et al., 2013*)**

w/c ratio	Age (days)	Control	RMA1	RMA2	CI-RMA1	CI-RMA2
0.50	3	1	0.79	0.89	0.94	0.92
	7	1	0.86	0.93	0.95	0.96
	28	1	0.91	0.94	0.95	0.99
	90	1	0.91	0.94	0.97	0.99



**Figure 2.14: Development of concrete's compressive strength, (*Shi-Cong et al., 2013*)**

*Seidemann et al. (2014)* studied the compressive strength behaviour of 5 concrete mixes named reference concrete using NA (RFB), concrete using 45% RCA (RB/45), concrete using 100% RCA (RB/100), concrete using 45% carbonated RCA (RBC/45) and concrete using 100% carbonated RCA (RBC/100) at age of 7, 14, 28 and 56 days, using w/c ratio of 0.5. It was observed that the compressive strength increases for all concrete as the progression of hydration time. When 45% of carbonated RCA was used, it was observed that no strength increases after 7 days only for the case of early strength. It was observed that when the recycled aggregates were present in higher contents in concrete, the carbonation process increases the strength more strongly.

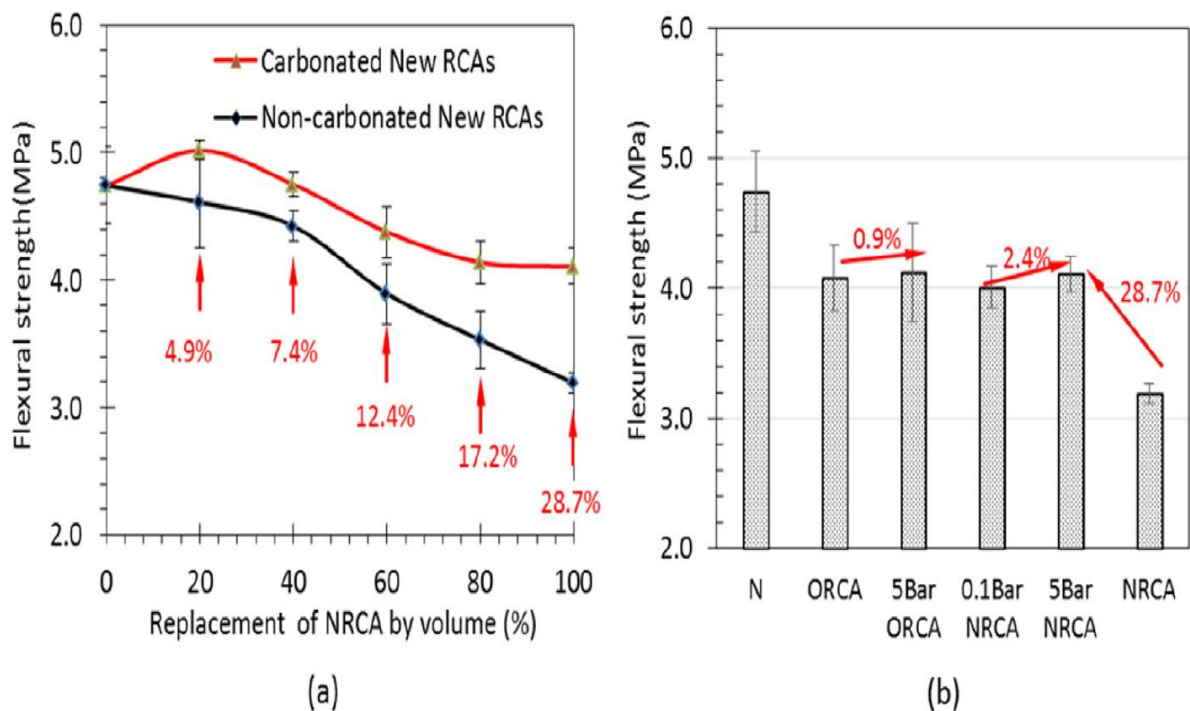


**Figure 2.15: Compressive strength of various types of concrete at 7, 14, 28 and 56 days, (*Seidemann et al., 2014*)**

### 2.3.1.2 Flexural Strength

*Xuan et al. (2015)* studied the flexural strength behaviour of various concrete mixes at 28 days, that were prepared by using various types of coarse aggregates named natural (N), old type of RCA (ORCA), new type of RCA (NRCA), carbonated ORCA at 5 bar pressure level, carbonated NRCA at 0.1 bar pressure level and carbonated NRCA at 5 bar pressure level, using w/c ratio of 0.55, superplasticizer to maintain slump in 150-200 mm range, also natural coarse

aggregates in concrete were replaced with other aggregates at 0%, 20%, 40%, 60%, 80% and 100%. An increase of 28.7% in flexural strength was found for concrete made by using 100% carbonated NRCA as compared to the concrete made by using 100% non-carbonated NRCA. When the natural aggregates were replaced with carbonated RCAs up to 60%, an insignificant reduction was observed in the flexural strength as compared to control concrete. Also, on properties of concrete, there was a lesser influence of carbonation pressure. Also, an increase in flexural strength of concrete made by using carbonated ORCA, there was a lesser influence of carbonation pressure.



**Figure 2.16: Flexural strength of concrete prepared by using carbonated and non-carbonated RCAs at 28 days, (Xuan et al., 2015)**

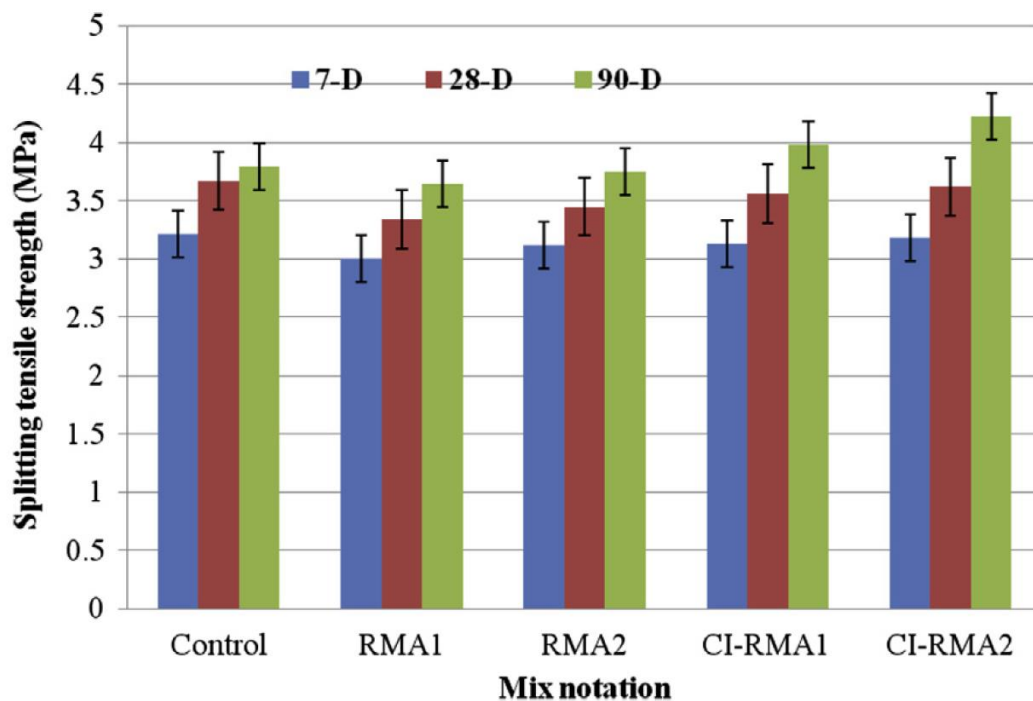
### 2.3.1.3 Split Tensile Strength

*Shi-Cong et al. (2013)* studied the splitting tensile strength behaviour of various types of concrete mixes named control (normal concrete), RMA1 (concrete containing recycled mortar aggregates of type-1), RMA2 (concrete containing recycled mortar aggregates of type-2), CI-RMA1 (concrete containing CO<sub>2</sub> improved recycled mortar aggregates of type-1), CI-RMA2 (concrete containing CO<sub>2</sub> improved recycled mortar aggregates of type-2), prepared by using w/c ratio of 0.5 for the age of 7, 28 and 90 days as shown in table 2.6 and figure 2.17. It was observed that the CI-RMA and RMA concrete mixes show less splitting tensile strength as compared to the control concrete before 28 days. Also, the CI-RMA1 and CI-RMA2 concrete

mixes show splitting tensile strengths that were 5% and 10% more as compared to the control concrete at 90 days. Therefore, it was observed that CO<sub>2</sub> curing regime enhanced the strength of the CI-RMA concrete mixes.

**Table 2.6: Relative concrete's splitting tensile strength, (Shi-Cong et al., 2013)**

w/c ratio	Age (days)	Control	RMA1	RMA2	CI-RMA1	CI-RMA2
0.50	7	1	0.93	0.97	0.98	0.99
	28	1	0.91	0.94	0.97	0.99
	90	1	0.96	0.99	1.05	1.11



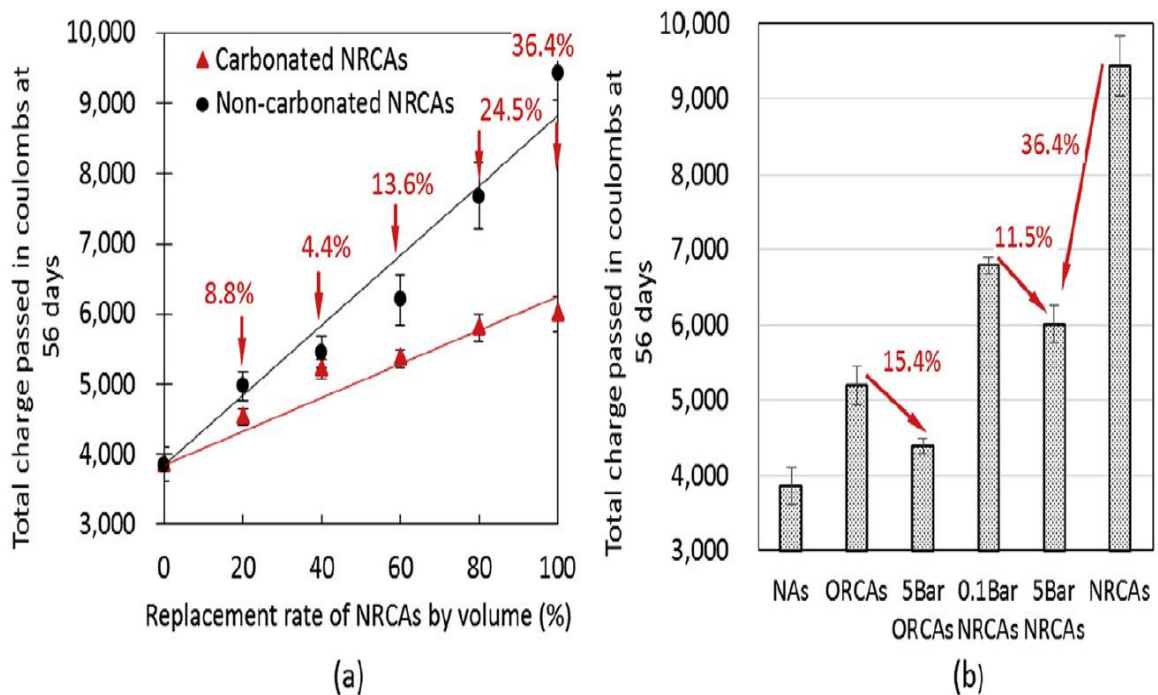
**Figure 2.17: Splitting tensile strength of concrete, (Shi-Cong et al., 2013)**

### 2.3.2 Durability Properties

#### 2.3.2.1 Rapid Chloride Permeability

*Xuan et al. (2017)* studied the resistance to chloride-ion penetration behaviour of various concrete mixes at 56 days, that were prepared by using various types of coarse aggregates named natural (N), non-carbonated old type of RCA (ORCA), non-carbonated new type of RCA (NRCA), carbonated ORCA at 5 bar pressure level, carbonated NRCA at 0.1 bar pressure

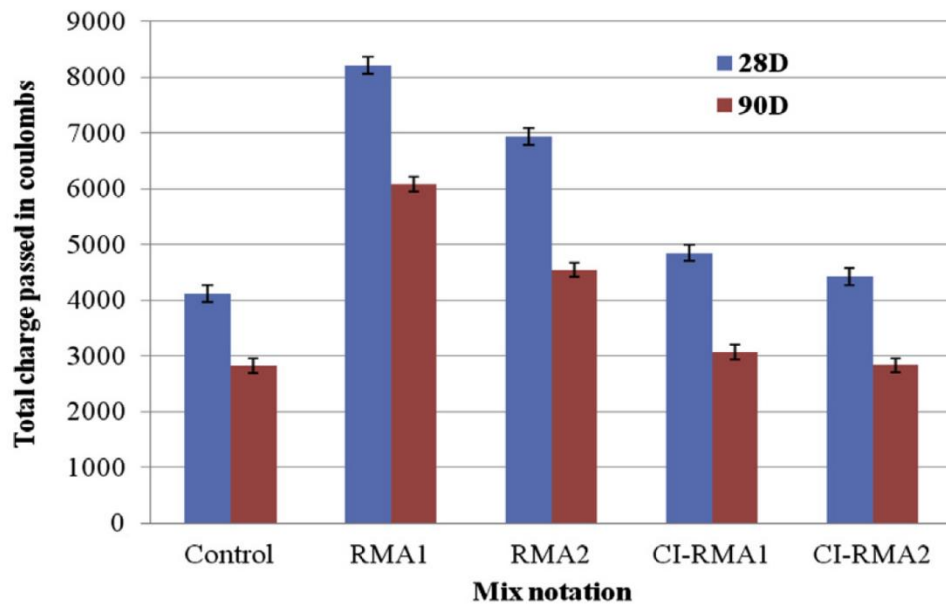
level and carbonated NRCA at 5 bar pressure level, using w/c ratio of 0.55, superplasticizer to maintain slump in 150-200 mm range, also natural coarse aggregates in concrete were replaced at 0%, 20%, 40%, 60%, 80% and 100% as shown in figure 2.18. A reduction of 36.4% in chloride penetration was observed for concrete made by using 100% carbonated NRCAs as compared to the concrete made by using non-carbonated NRCAs at 56 days. But, as compared to the normal concrete made by using only NAs, this value was still approximately 1.5 times more. An increase in resistance to chloride-ion penetration and a reduction of 15.4% was found in total charge passed when concrete made by using carbonated ORCAs.



**Figure 2.18: Total charge passed in coulombs for concretes prepared by using natural aggregates, non-carbonated RCAs and carbonated RCAs at 56 days, (Xuan et al., 2017)**

*Shi-Cong et al. (2013)* studied the resistance to chloride-ion penetration behaviour of various types of concrete mixes named control (normal concrete), RMA1 (concrete containing recycled mortar aggregates of type-1), RMA2 (concrete containing recycled mortar aggregates of type-2), CI-RMA1 (concrete containing CO<sub>2</sub> improved recycled mortar aggregates of type-1), CI-RMA2 (concrete containing CO<sub>2</sub> improved recycled mortar aggregates of type-2), prepared by using w/c ratio of 0.5 for the age of 28 and 90 days. It was observed that in concrete mixes by using the CI-RMA, chloride-ion penetration resistance was increased as compared to the RMA concrete mixes. CI-RMA1 and CI-RMA2 concrete mixes show 41% and 46% more chloride-ion penetration resistance as compared to the RMA1 and RMA2 concrete mixes, respectively

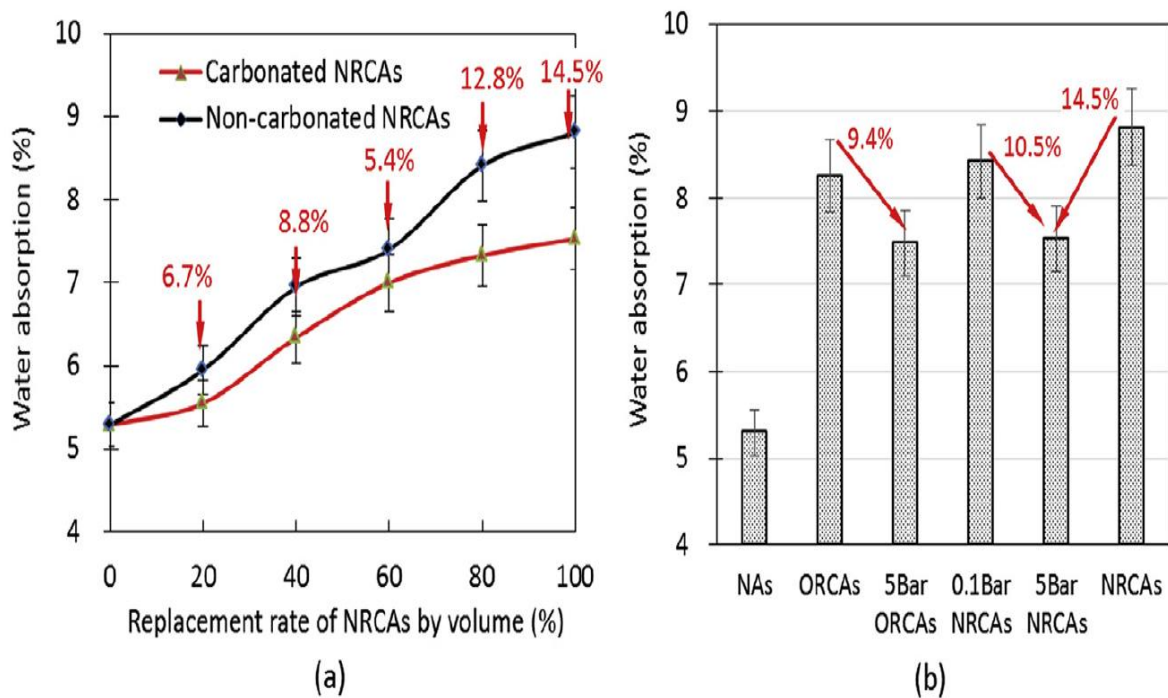
at 28 days, and values are similar as compared to the control concrete. Therefore, it was observed that the water absorption of RMA concrete mixes enhanced by the CO<sub>2</sub> curing regime.



**Figure 2.19: Total charge passed in terms of coulombs for various types of concrete, (Shi-Cong et al., 2013)**

### 2.3.2.2 Water Absorption

Xuan et al. (2017) studied the water absorption behaviour of various concrete mixes at 56 days, that were prepared by using various types of coarse aggregates named natural (N), un-



**Figure 2.20: Water absorption for concretes prepared by using natural aggregates, non-carbonated RCAs and carbonated RCAs at 56 days, (Xuan et al., 2017)**

carbonated old type of RCA (ORCA), non-carbonated new type of RCA (NRCA), carbonated ORCA at 5 bar pressure level, carbonated NRCA at 0.1 bar pressure level and carbonated NRCA at 5 bar pressure level, using w/c ratio of 0.55, superplasticizer to maintain slump in 150-200 mm range, also natural coarse aggregates in concrete were replaced at 0%, 20%, 40%, 60%, 80% and 100% as shown in figure 2.20. A reduction of 10.5% was found in water absorption of RAC when carbonation pressure is increased from 0.1 to 5 bars of NRCAs. A reduction of 9.4% in water absorption of RAC was found when using concrete made with 100% ORCAs, also it was less as compared to the RAC made by using 100% carbonated ORCAs. For RAC, an increase in water absorption was found when NAs were replaced from 0-100% by RCAs in normal concrete. A decrease was observed in water absorption of RAC when carbonation of RCAs was done.

## CHAPTER 3

### EXPERIMENTAL PROGRAMME

#### 3.1 GENERAL

The various details regarding the research work such as material properties, mix design, casting of specimens, the test set-up and testing procedure for different properties have been discussed in this chapter.

#### 3.2 EXPERIMENTAL DETAILS

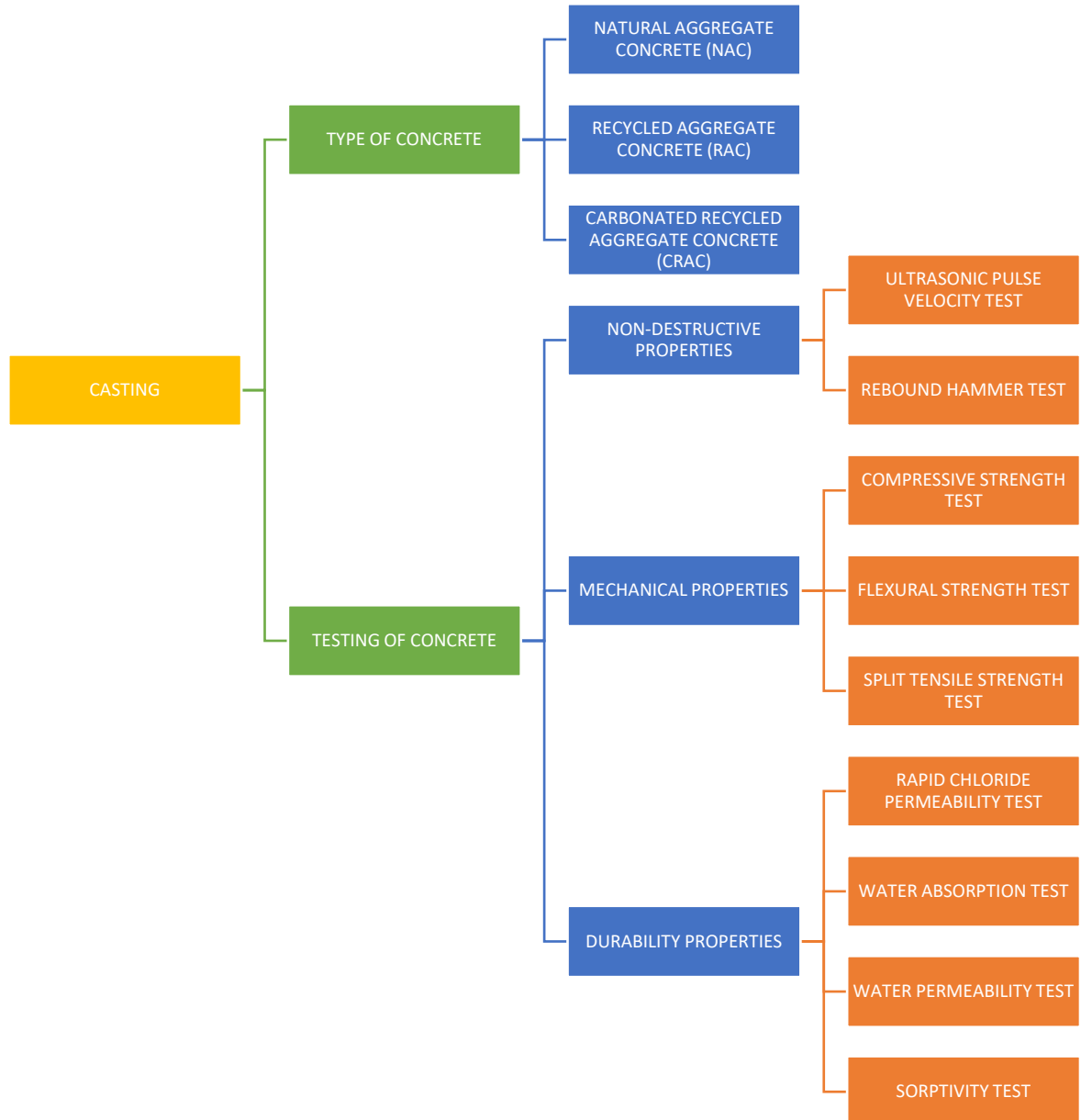


Figure 3.1: Flow-chart of Experimental Programme

The experimental programme presenting the details regarding the various types of concrete casted and the various types of testing (non-destructive, mechanical & durability) done on casted specimens.

### 3.3 MATERIAL PROPERTIES

The various construction materials like cement, water, fine aggregate, natural coarse aggregate, recycled coarse aggregate and carbonated recycled coarse aggregate have been used in this research work. The physical properties of these materials are presented in these coming paragraphs.

#### 3.3.1 Cement

Cement is a grey coloured finely ground powder. To make the concrete mix, it is added with various construction materials like sand, water, coarse aggregates in different amounts depending on the mix ratio of concrete. As the concrete starts hardening, water and cement make a paste which binds together all the other materials present in the concrete mix. The calcareous and argillaceous are 2 basic ingredients which are carried by any ordinary cement. Calcium carbonate predominates in calcareous materials and clay predominates in argillaceous materials. Conforming to requirements of IS 8112 : 1989, the Ordinary Portland cement (OPC) of grade-43 of the brand name “Ambuja” have been used in this research work. On cement properties, the results of some tests performed are given in Table 3.1.

**Table 3.1: Physical properties of cement used**

S.No.	Characteristics	Values obtained	Values as per IS 8112 : 1989
1.	Consistency	28.9 %	-
2.	Initial setting time	123 minutes	Not less than 30 minutes
3.	Final setting time	192 minutes	Not more than 600 minutes
4.	Fineness	283.7 m <sup>2</sup> /kg	Not less than 225 m <sup>2</sup> /kg
5.	Specific gravity	3.06	-

#### 3.3.2 Fine Aggregate

The material that passes from the 4.75 mm sieve and retained on 150 microns sieve is known as fine aggregate. Normally, as a fine aggregate, natural sand is used. As a fine aggregate, crushed stone is used where the natural sand is unavailable. The natural sand that is used in this

research work is obtained from nearby sources and also conformed to IS : 383-1970 (grading zone II) specifications. For fine aggregate, the sieve analysis is shown in Table 3.2 and the physical properties in Table 3.3.

**Table 3.2: Sieve analysis of fine aggregate**

S.No.	Sieve size (mm)	Weight retained (grams)	Retained (%)	Passing (%)	Cumulative weight retained (grams)	Cumulative (%) retained
1.	4.75	31	3.1	96.9	31	3.1
2.	2.36	137	13.7	83.2	168	16.8
3.	1.18	238	23.8	59.4	406	40.6
4.	600 microns	168	16.8	42.6	574	57.4
5.	300 microns	316	31.6	11	890	89
6.	150 microns	65	6.5	4.5	955	95.5
7.	pan	45	4.5	0	1000	-
						Sum = 302.4

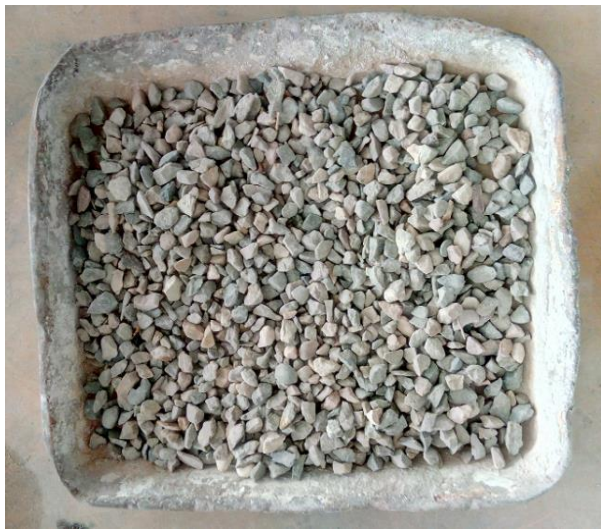
$$\text{Fineness modulus of fine aggregate} = \frac{\text{Sum}}{100} = \frac{302.4}{100} = 3.024$$

**Table 3.3: Physical properties of fine aggregate**

S.No.	Characteristics	Value
1.	Type	Natural
2.	Specific gravity	2.54
3.	Fineness modulus	3.02
4.	Grading zone	Type II
5.	Water Absorption	1.02 %

### 3.3.3 Natural Coarse Aggregate (NCA)

Normally, the broken stone is used as a natural coarse aggregate. The maximum size of natural coarse aggregate is decided by the nature of its work. Aggregates having a maximum size of 10 mm & 20 mm, that are available from nearby sources are used in this research work. For natural coarse aggregate, the sieve analysis is shown in Table 3.4 for the maximum size of 10 mm & Table 3.5 for the maximum size of 20 mm.



(a)



(b)

**Figure 3.2:** Shows the natural coarse aggregates of (a) 10 mm maximum size and (b) 20 mm maximum size

**Table 3.4:** Sieve analysis of 10 mm maximum size natural coarse aggregate

S.No.	Sieve size (mm)	Weight retained (kg)	Retained (%)	Passing (%)	Cumulative weight retained (kg)	Cumulative (%) retained
1.	10	3.365	33.650	66.350	3.365	33.650
2.	4.75	5.457	54.570	11.780	8.822	88.220
3.	Pan	1.158	11.580	0.000	9.980	-
						Sum = 121.87

$$\text{Fineness modulus} = \frac{121.87 + 500}{100} = 6.218$$

**Table 3.5 :** Sieve analysis of 20 mm maximum size natural coarse aggregate

S.No.	Sieve size (mm)	Weight retained (kg)	Retained (%)	Passing (%)	Cumulative weight retained (kg)	Cumulative (%) retained
1.	20	0.395	3.950	96.050	0.395	3.950
2.	10	8.973	89.730	6.320	9.368	93.680
3.	4.75	0.578	5.780	0.540	9.946	99.460
4.	Pan	0.048	0.480	0.000	10.000	-
						Sum = 197.09

$$\text{Fineness modulus} = \frac{197.09 + 500}{100} = 6.970$$

### 3.3.4 Recycled Coarse Aggregate (RCA)

Large quantities of tested specimens of concrete like beams, cylinders and cubes etc. of different sizes were placed outside of the concrete lab of Thapar University. These specimens were used to make the recycled coarse aggregates (RCA) in the lab. Firstly, the specimens were broken down into small pieces manually, which were without reinforcement. Then, crushed that broken pieces by putting them in a jaw crusher as shown in Figure 3.4. Then, the crushed concrete pieces, depending on their size, were separated into 2 fractions.



**Figure 3.3: Waste concrete pieces used for making recycled coarse aggregates**



**Figure 3.4: Using a jaw crusher to make recycled coarse aggregates**



**Figure 3.5: Sieving work after making recycled coarse aggregates with jaw crusher**

The fraction that passes through 20 mm sieve and then retained on 10 mm sieve was classified as RCA20-10 mm and the other fraction that passes through 10 mm sieve and then retained on 4.75 mm sieve was classified as RCA10-4.75 mm. The fraction that passes from the 4.75 mm sieve was rejected. RCA's of two different sizes were mixed in suitable amounts while making the RCA concrete so that for the combined RCA concrete, the gradation curve was identical to that of NCA.



**(a)**

**(b)**

**Figure 3.6: Shows the recycled coarse aggregates of (a) 10 mm maximum size and (b) 20 mm maximum size**

**Table 3.6: Sieve analysis of 10 mm maximum size recycled coarse aggregate**

S.No.	Sieve size (mm)	Weight retained (kg)	Retained (%)	Passing (%)	Cumulative weight retained (kg)	Cumulative (%) retained
1.	10	0.210	2.100	97.900	0.210	2.100
2.	4.75	8.900	89.000	8.900	9.110	91.100
3.	Pan	0.900	9.000	0.000	10.000	-
						Sum = 93.20

$$\text{Fineness modulus} = \frac{93.20 + 500}{100} = 5.932$$

**Table 3.7 : Sieve analysis of 20 mm maximum size recycled coarse aggregate**

S.No.	Sieve size (mm)	Weight retained (kg)	Retained (%)	Passing (%)	Cumulative weight retained (kg)	Cumulative (%) retained
1.	20	0.290	2.900	97.100	0.290	2.900
2.	10	8.840	88.400	8.700	9.130	91.300
3.	4.75	0.795	7.950	0.750	9.925	99.250
4.	Pan	0.070	0.700	0.000	10.000	-
						Sum = 193.45

$$\text{Fineness modulus} = \frac{193.45 + 500}{100} = 6.934$$

**Residual Mortar Test:** Also, the residual mortar (or mortar content test) is done on the recycled coarse aggregates to determine the amount of mortar attached to the recycled coarse aggregates. For this test, three plastic bathing mugs are used.

In each mug, a total of 400 grams of recycled coarse aggregates (60% of 20 mm size and 40% of 10 mm size) are placed. Now, make a solution in which half the quantity of water and half quantity of HCL acid is used. Then, using this solution dip all aggregates placed in three mugs for about 48 hours as shown in Figure 3.8. Also, stir the aggregates placed in acidic solution in mugs after 24 hours with a wooden stick. After 48 hours, remove and wash the aggregates with clean water. Then, place the aggregates in the oven drying for about 24 hours. Then, note the weights of dried samples and calculate the mortar content present on recycled coarse aggregates.



**Figure 3.7: Three plastic bathing mugs used, in which recycled coarse aggregates are dipped in an acidic solution**



**Figure 3.8: Recycled coarse aggregates (60% of 20 mm size and 40% of 10 mm size) dipped in an acidic solution (half quantity of water and half quantity of HCL acid)**

The calculations of this test are following:

Original weight of 3 Aggregates sample taken,  $M_0 = 400 + 400 + 400 = 1200$  g

Combined weight of 3 Aggregates sample after oven dry,  $M_1 = 650$  g

$$\begin{aligned}\% \text{ Mortar Content} &= \frac{M_0 - M_1}{M_0} \times 100 \\ &= \frac{1200 - 650}{1200} \times 100 \\ &= 45.83 \%\end{aligned}$$

### 3.3.5 Carbonated Recycled Coarse Aggregate (CRCA)

For the preparation of carbonated recycled coarse aggregates (CRCA), an airtight steel-cubical carbonation chamber along with CO<sub>2</sub> cylinder was used. Figure 3.9 shows setup used for carbonation curing of recycled coarse aggregates (RCA) in this study. The carbonation chamber was provided with the vacuum motor, vacuum pipe and valve, safety valve, pressure gauges, heater, CO<sub>2</sub> cylinder with pipe and regulator, silica gel. The carbonation chamber was connected to the CO<sub>2</sub> cylinder having a concentration of 99% of industrial grade CO<sub>2</sub> gas.



**Figure 3.9: Carbonation chamber along with CO<sub>2</sub> cylinder used in this study**

Recycled coarse aggregates (RCA) of the maximum size of 10 mm & 20 mm both were treated with CO<sub>2</sub> gas in the carbonation chamber to prepare Carbonated Recycled Coarse Aggregate (CRCA) of both sizes. To facilitate the carbonation process and to reduce free water content in aggregates, firstly the recycled coarse aggregates (RCA) were dried in ambient conditions (temperature  $25\pm 3^{\circ}\text{C}$  and RH 40-70%) for about 6 hours.

Then, the aggregates sample was placed in the chamber and closed the chamber opening by tightening of its screws. Then, before the injection of CO<sub>2</sub> gas into the chamber, it was vacuumed to -0.46 bar (-350 mmHg) by using a vacuum motor. Then, the CO<sub>2</sub> gas in the cylinder was heated for about 5 minutes by using a heater attached to the cylinder. Then, at a pressure level of 2.76 Bar (40 psi), the CO<sub>2</sub> gas having a concentration of 99% was injected into the chamber. With the help of pressure gauges, at the curing chamber and at the CO<sub>2</sub> cylinder, the pressure was maintained. For about 48 hours in the carbonation chamber, the RCAs were carbonated in this study. To absorb the water evaporated from aggregates, at the bottom of the carbonation chamber, enough amount of silica gel was placed. Until enough quantities of CRCA were obtained, the above steps were repeated.



**Figure 3.10:** Shows the carbonated recycled coarse aggregates of (a) 10 mm maximum size and (b) 20 mm maximum size

**Table 3.8:** Physical properties of Natural, Recycled and Carbonated Recycled coarse aggregates

S.No.	Properties of Aggregates	Natural Coarse Aggregate (NCA)	Recycled Coarse Aggregate (RCA)	Carbonated Recycled Coarse Aggregate (CRCA)
1.	Specific gravity	2.752	2.276	2.568
2.	Water absorption (%)	1.419	11.648	8.923
4.	Impact value (%)	13.749	24.244	16.946
5.	Crushing value (%)	19.996	30.857	23.428

### 3.3.6 Water

Water is a major component of concrete because in the chemical reaction along with the cement it actively participates. The quality and quantity of water should be looked into very carefully because water helps to achieve the strength by forming cement gel. Potable water is normally considered adequate. In this research, tap water is used for curing, mixing and testing purposes.

### 3.4 MIX DESIGN

Design of the concrete mix proportion was done carefully by following the authorized guidelines of IS 10262 : 2009. A total of three mix combinations named NAC (using 100% natural coarse aggregate), RAC (using 100% recycled coarse aggregate) and CRAC (using 100% carbonated recycled coarse aggregate) were prepared by keeping the cement, fine aggregate and water content constant in all mixes. In the NAC mix, only natural coarse aggregates of maximum size 10 mm (40% of the weight of total coarse aggregates) and 20 mm (60% of the weight of total coarse aggregates) were used. In the RAC mix, only recycled coarse aggregates of maximum size 10 mm (40% of the weight of total coarse aggregates) and 20 mm (60% of the weight of total coarse aggregates) were used. In the CRAC mix, only carbonated recycled coarse aggregates of maximum size 10 mm (40% of the weight of total coarse aggregates) and 20 mm (60% of the weight of total coarse aggregates) were used. The various concrete mix proportions are presented in Table 3.11. The desired workability for the concrete mixes was kept at 90-100 mm slump. Recycled aggregates and carbonated recycled aggregates were firstly pre-soaked for 24 hrs to compensate for the recycled aggregate's additional water requirement and sun-dried before use in the concrete mixes. For preparing any concrete mix, hand mixing of the material was done. Firstly, the dry mix was prepared by adding coarse aggregates (10 mm & 20 mm), fine aggregate and cement, then the required amount of water was added and mixed thoroughly for creating a homogeneous mix. The mix design requirement is represented below:

**Table 3.9: Mix Design Requirements**

<b>Characteristic strength at 28 days</b>	30 MPa
<b>Max. size of aggregates</b>	20 mm
<b>Type of exposure</b>	Moderate (RCC)

**Table 3.10: Mix Proportion (M30)**

<b>Cement</b>	<b>Fine Aggregate</b>	<b>Coarse Aggregate (10 mm)</b>	<b>Coarse Aggregate (20 mm)</b>	<b>Water</b>
1	1.82	0.9	1.35	0.48

**Table 3.11: Concrete Mix Proportions**

<b>Mix</b>	<b>NAC</b>	<b>RAC</b>	<b>CRAC</b>
<b>Replacement (%)</b>	-	100	100
<b>Cement (kg/m<sup>3</sup>)</b>	420	420	420
<b>Fine Aggregate (kg/m<sup>3</sup>)</b>	765	765	765
<b>Natural Coarse Aggregate (kg/m<sup>3</sup>) (10 mm)</b>	378	-	-
<b>Natural Coarse Aggregate (kg/m<sup>3</sup>) (20 mm)</b>	567	-	-
<b>Recycled Coarse Aggregate (kg/m<sup>3</sup>) (10 mm)</b>	-	378	-
<b>Recycled Coarse Aggregate (kg/m<sup>3</sup>) (20 mm)</b>	-	567	-
<b>Carbonated Recycled Coarse Aggregate (kg/m<sup>3</sup>) (10 mm)</b>	-	-	378
<b>Carbonated Recycled Coarse Aggregate (kg/m<sup>3</sup>) (20 mm)</b>	-	-	567
<b>Water (kg/m<sup>3</sup>)</b>	205	205	205

### **3.5 CURING OF SPECIMENS**

Curing should be done with utmost care for the concrete specimens to attain its required strength. The concrete may lose moisture and therefore it will not be able to achieve to the required strength if the curing is not done properly.

Firstly, the samples were cast and remain in the moulds for about 24 hours for hardening of concrete, then the hardened concrete samples were removed from the moulds and immediately placed in the curing tank. All types of sample were allowed to remain in the curing tank for 28 days and then the required testing of specimens was done.



**Figure 3.11: Curing of the samples in water tanks**

### **3.6 TESTING OF SPECIMENS**

In this section test setup for various non-destructive properties (Ultrasonic pulse velocity, Rebound hammer), mechanical properties (Compressive strength, Flexural strength, Split tensile strength) and durability properties (Rapid chloride permeability, Water absorption, Water permeability, Sorptivity) of concrete are discussed.

**Table 3.12: Tests performed and codes followed**

<b>S.No.</b>	<b>Test</b>	<b>Code</b>
1.	Ultrasonic pulse velocity test	IS 13311 (Part 1) : 1992
2.	Rebound hammer test	IS 13311 (Part 2) : 1992
3.	Compressive strength test	IS : 516 - 1959
4.	Flexural strength test	IS : 516 - 1959
5.	Split tensile strength test	IS 5816 : 1999
6.	Rapid chloride permeability test	ASTM C1202 - 12
7.	Water absorption test	ASTM C 642 - 97
8.	Water permeability test	German standard DIN 1048 (Part 5)
9.	Sorptivity test	ASTM C 1585 - 04

### **3.6.1 Non-Destructive properties**

#### **3.6.1.1 Ultrasonic pulse velocity test**

Ultrasonic pulse velocity was determined in this test as per procedure is given in IS 13311 (Part 1) : 1992. The apparatus required to perform this test includes an electrical pulse generator, amplifier, electronic timing device, cube specimens and transducer (one pair). To measure the ultrasonic pulse velocity passing along the concrete, cubes of size 150×150×150 mm were used. This test was performed at the end of curing age of 28 days on all types of concrete mixes (NAC, RAC, and CRAC). For this test, an Ultrasonic Non-destructive Digital Indicating Tester (Battery operated and Portable) was used. Longitudinal stress wave's pulses that were generated by an electro-acoustical transducer which was held in contact with concrete's one face and another transducer received it which was held in contact with concrete's other face. To pass through the specimen having a length (L), the time (T) taken by the pulse is known as transit time. The pulse velocity (V) is calculated by:

$$V = \frac{L}{T}$$

For each type of concrete mix, 3 cubes were tested and 3 readings were taken on each cube. An average of 3 readings was taken for each cube. For the pulse velocity of concrete mix, the average value of 3 specimens was taken. The apparatus used in this test is shown in Figure 3.12 and 3.13.

**Table 3.13: Concrete Quality Grading as per IS 13311 (Part 1) : 1992**

Pulse Velocity (m/s)	Concrete Quality Grading
Above 4500	Excellent
3500 – 4500	Good
3000 – 3500	Medium
Less than 3000	Doubtful



**Figure 3.12: Testing set up for determining ultrasonic pulse velocity through concrete**



**Figure 3.13: Readings shown by Ultrasonic digital instrument**

### **3.6.1.2 Rebound hammer test**

Rebound hammer test was performed on concrete cube specimens to determine the compressive strength of concrete as per procedure is given in IS 13311 (Part 2) : 1992. The apparatus required to perform this test include rebound hammer, digital instrument, CTM and cube specimens. For this test, cubes of size 150×150×150 mm were used. This test was performed at the end of curing age of 28 days on all types of concrete mixes (NAC, RAC, and CRAC). Against the surface of concrete, when rebound hammer's plunger was pressed, the spring-controlled mass rebounds. On the surface hardness of concrete, the range of such a rebound depends. Therefore, the compressive strength of concrete can be related to the rebound. From the graduated scale, rebound value can be read and designated as rebound index or rebound number. The compressive strength value can be read from the digital instrument. Apply the light pressure on the plunger of the rebound hammer, this will release the plunger from the locked position. Firstly, cube specimen was fixed under the CTM by applying some load and then paused the machine for rebound hammer test. Then, by keeping the instrument perpendicular to the surface of testing, the plunger was pressed against the concrete's surface. A gradual increase in pressure was applied until the hammer impacts.

For each type of concrete mix, 3 cubes were tested and 5 readings were taken on each cube, the point of impact should be 20 mm away at least, from any edge. An average of 5 readings

was taken for each cube. And an average of 3 cubes was taken for compressive strength value of any mix.



(a)



(b)

**Figure 3.14 : (a) Performing the rebound hammer test on concrete cube specimen and (b) test readings shown by digital instrument**

### 3.6.2 Mechanical properties

#### 3.6.2.1 Compressive strength test

The compressive strength of concrete specimens was determined in this test as per IS : 516 – 1959. The apparatus required to perform this test include cube moulds of size 150×150×150 mm, tamping rod, mixing container, compression testing machine (CTM) and weighing machine. To measure the compressive strength of concrete, cubes of size 150×150×150 mm were used. This test was performed at the end of curing age of 28 days on all types of concrete mixes (NAC, RAC, and CRAC). After completion of curing age of 28 days, the cubes were removed from curing tanks and placed outside for 10 minutes for surface-drying of cubes. Then, the cube was placed under the compression testing machine (CTM) having a capacity of 5000 KN as shown in Figure 3.15 in such a way that the load was applied to that surface of the cube which was perpendicular to the casted surface of the cube. The load was applied without providing any shock to the specimen and continuously increased at the loading rate of 5 KN/s. Peak load on the specimen was considered as that load above which it failed to take any load.



**Table 3.15: Testing of a cube for compressive strength using CTM**

For each type of concrete mix, 3 cubes were tested. For the compressive strength of the concrete mix, the average value of 3 specimens was taken. The formula for calculating compressive strength is shown below:

$$f_{ck} = \frac{P}{A}$$

where,

$A = 150 \times 150 \times 150$  mm size of cube's surface area ( $\text{mm}^2$ )

$P =$  Maximum load applied (N)

$f_{ck} =$  Compressive strength ( $\text{N}/\text{mm}^2$ )

### **3.6.2.2 Flexural strength test**

Flexural strength of concrete specimens was determined in this test as per IS : 516 – 1959. To measure the flexural strength of concrete, beams of size  $700 \times 150 \times 150$  mm were used. The apparatus required to perform this test included moulds of size  $700 \times 150 \times 150$  mm, tamping rod, mixing container, table vibrator, universal testing machine (UTM), two steel rollers and weighing machine. This test was performed at the end of curing age of 28 days on all types of concrete mixes (NAC, RAC, and CRAC). After completion of curing age of 28 days, the beams were removed from curing tanks and placed outside for some time for surface-drying of beams. Then, the beam was placed under the universal testing machine (UTM) as shown in Figure 3.16. In such a manner, the specimen shall be placed under machine that the load shall be applied to the casted surface, along two lines that were 20 cm apart. The axis of the loading device shall be carefully aligned with the axis of specimen. Between the bearing surfaces of rollers and specimen, no packing shall be used. Two-point loading system was used in this test. The load was applied without providing any shock to specimen and continuously increased at the loading rate of 400 kg/min. Peak load on the specimen was considered as that load above which it failed to take any load.

For each type of concrete mix, 3 beams were tested. For the flexural strength of the concrete mix, the average value of 3 specimens was taken. The formula for calculating flexural strength is shown below:

$$f_b = \frac{pl}{bd^2}$$

where,

$d =$  Measured depth of specimen at failure point (mm)

$b =$  Measured width of specimen (mm)

$l =$  Length of span on which specimen was supported (mm)

$p =$  Maximum load applied to specimen (N)

$f_b$  = Flexural strength (N/mm<sup>2</sup>)



**Figure 3.16: Testing of a beam for flexural strength on UTM**

### **3.6.2.3 Split tensile strength**

The split tensile strength of concrete specimens was determined in this test as per IS 5816 : 1999. To measure the split tensile strength of concrete, cylinders of diameter 100 mm and height 200 mm were used. The apparatus required to perform this test includes cylinder moulds of diameter 100 mm and height 200 mm, tamping rod, mixing container, compression testing machine (CTM), and weighing machine. This test was performed at the end of curing age of 28 days on all types of concrete mixes (NAC, RAC, and CRAC). After completion of curing age of 28 days, the cylinders were removed from curing tanks and placed outside for some time for surface-drying of cylinders. Then, the cylinder was placed under the compression testing machine (CTM) having a capacity of 5000 KN as shown in Figure 3.17. The load was applied without providing any shock to specimen and continuously increased at the loading rate of 1 KN/s. Peak load on the specimen was considered as that load above which it failed to take any load.

For each type of concrete mix, 3 cylinders were tested. For the split tensile strength of concrete mix, the average value of 3 specimens was taken. The formula for calculating split tensile strength is shown below:

$$f_{ct} = \frac{2P}{\pi ld}$$

where,

$d$  = Cross sectional dimension of specimen (mm)

$l$  = Length of specimen (mm)

$P$  = Maximum load applied to specimen (N)

$f_{ct}$  = Split tensile strength (N/mm<sup>2</sup>)



**Figure 3.17: Testing of a cylinder for split tensile strength on CTM**

### **3.6.3 Durability properties**

#### **3.6.3.1 Rapid chloride permeability test**

The rapid chloride permeability test was done for the determination of concrete's electrical conductance which further indicates its resistance to chloride ions penetration. This test was

done as per the procedure shown in ASTM C1202 – 12. A concrete cylinder (diameter 100 mm and height 200 mm) was cut into slices of diameter 100 mm and height 50 mm to prepare samples for this test. The apparatus required to perform this test include concrete specimens, RCPT test machine, Vacuum desiccator’s bowl, grease, distilled water, funnel, empty beakers, NaOH solution, and NaCl solution. This test was performed at the end of curing age of 28 days on all types of concrete mixes (NAC, RAC, and CRAC).

As shown in Figure 3.18, first of all, the specimens were put inside the vacuum desiccator’s bowl. In the vacuum desiccator’s bowl, the vacuum was maintained for 3 hours. Into the desiccator, the flow of de-aerated water was allowed because it totally covers the concrete specimens and entry of no air was allowed. Then, the concrete samples were removed from vacuum desiccator’s bowl, then surface dried, then mounted into the gasket. Across the ends of the specimen, a potential difference of 60 Volt (DC) was provided. Two solutions were filled in each testing mould. Sodium chloride solution (3% NaCl solution) used for immersion of one end of specimen and Sodium hydroxide solution (0.3N NaOH solution) used for immersion of another end of the specimen. In this test, the amount of electrical current passed from the concrete specimen was monitored for a 6-hour period. In this study for measuring chloride ion penetration, “PROOVE it” data processor was used as shown in Figure 3.19. According to Table 3.14, on the basis of charge passed, the chloride ion penetrability was decided.

For each type of concrete mix, 3 specimens were tested. For the chloride ion penetrability of concrete mix, the average value of 3 specimens was taken.

**Table 3.14: Based on charge passed through the specimen, the extent of chloride ion penetrability of concrete as per ASTM C1202 - 12**

Charge Passed (coulombs)	Chloride Ion Penetrability
> 4000	High
2000 – 4000	Moderate
1000 – 2000	Low
100 – 1000	Very Low
< 100	Negligible



**Figure 3.18: Concrete specimens in the vacuum desiccator's bowl**



**Figure 3.19: Test setup for the rapid chloride permeability test**

### **3.6.3.2 Water absorption test**

The water absorption of concrete was determined in this test as per ASTM C 642 – 97. To measure water absorption of concrete, cubes of size 150×150×150 mm were used. The apparatus required to perform this test include cubes moulds of size 150×150×150 mm, tamping rod, mixing container, curing tank filled with water, oven and weighing machine. This test was performed at the end of curing age of 28 days on all types of concrete mixes (NAC, RAC, and CRAC). After completion of curing age of 28 days, the cubes were removed from curing tanks and placed outside for some time for surface-drying of cubes. Then, for a period

of 24-hour at a temperature of 110°C, the specimens were oven dried. Then, they were cooled down to room temperature and measure its weights. Then, for a period of 48-hour at a temperature of approximately 21°C, the specimens were immersed in water in the curing tanks. Then, after 48 hours the cubes were removed from curing tanks and surface dried, then measure its weights. For each type of concrete mix, 3 cubes were tested. For the water absorption of concrete mix, the average value of 3 specimens was taken. The formula for calculating the water absorption of concrete is shown below:

$$W_A = \frac{w_{SSD} - w_{OD}}{w_{OD}} \times 100 \%$$

where,

$w_{SSD}$  = weight of the saturated surface dry sample (grams)

$w_{OD}$  = weight of oven dried sample (grams)

$W_A$  = Water absorption (%)

### **3.6.3.3 Water permeability test**

In this test, the water permeability of concrete specimens was checked as per German standard DIN 1048 (Part 5). For this test, cubes of size 150×150×150 mm were used. The apparatus required to perform this test include concrete cube of size 150×150×150 mm, pressure regulator, water penetration cell, water reservoir with water regulator, beaker, funnel, oven, wrench, CTM, black marker and scale. This test was performed at the end of curing age of 28 days on all types of concrete mixes (NAC, RAC, and CRAC). After completion of curing age of 28 days, the cubes were removed from curing tanks and placed outside for 10 minutes for surface-drying of cubes.

Firstly, the specimens were dried in the oven for about 24 hours, then placed them outside for cool down at room temperature. Then, the water reservoir was filled up to 75%, then the specimen was placed in the water penetration cell. The specimen was placed in that way that the cast surface of the cube was perpendicular to the test surface. Then, the nuts were tightened by using a wrench, then the valve of water regulator was opened. Then, the pressure valve was opened and by using a pressure regulator, the pressure was set to 5 kg/cm<sup>2</sup>. By maintaining this pressure, this test was performed for a period of 72 hours (3 days). After 3 days, the specimen was removed from the cell and placed under the CTM. Then, the specimen was split in a

direction perpendicular to the injected face and the depth of penetration was determined visually.

In this test, water under the pressure was applied on the one surface of the concrete cube for a particular period of time, then split the specimen to determine its depth of penetration. The test cell assembly that was used in this test had the provision for testing three cube specimens at the same time. For each type of concrete mix, 3 cubes were tested. For determining the water penetration depth of the concrete mix, the average value of 3 specimens was taken.



**Figure 3.20: Test setup for the water permeability test**



**Figure 3.21: Splitting the cube specimen under CTM after removing from the water penetration cell**



**Figure 3.22: Measuring the water penetration depth with scale**

### 3.6.3.4 Sorptivity test

Against the penetration of water, to check the sensitivity of an unsaturated concrete specimen, this test was performed. Water Sorptivity of concrete specimens was determined in this test as per ASTM C 1585 – 04. A concrete cylinder (diameter 100 mm and height 200 mm) was cut into slices of diameter 100 mm and height 50 mm to prepare samples for this test. The apparatus required to perform this test include concrete specimens, pan, water, support device (rod), weighing balance, timing device, paper towel or cloth, epoxy, duct tape, plastic bag or sheeting and permanent marker. This test was performed at the end of curing age of 28 days on all types of concrete mixes (NAC, RAC, and CRAC).

At a temperature of  $50 \pm 2^\circ\text{C}$ , concrete specimens were oven dried for 3 days. Then, for 15 days in the sealable container, the specimen was placed. Then, the weight of specimen was recorded up to the accuracy of 0.001g and sides of the specimen were sealed by using epoxy and duct tape. To prevent evaporation of water, a plastic sheet was attached at the top of the specimen. Then, the mass of sealed specimen was measured and noted this mass as an initial mass. Then, the specimens were placed in water as shown in Figure 3.23 and to note the time stopwatch was started. The concrete specimen's mass was noted at an interval of 1, 5, 10, 20 and 30 minutes, then 1, 2, 3, 4, 5 and 6 hours, then 1, 2, 3, 5, 6, 7 and 8 days.

For each type of concrete mix, 3 specimens were tested. For the sorptivity of the concrete mix, the average value of 3 specimens was taken. The formula for calculating the absorption is shown below:

$$I = \frac{m_t}{a \times d}$$

where,

$d$  = the density of water ( $\text{g}/\text{mm}^3$ )

$a$  = the specimen's exposed area ( $\text{mm}^2$ )

$m_t$  = at time  $t$ , change in specimen mass (g)

$I$  = the absorption (mm)



**Figure 3.23: Testing setup for performing sorptivity of concrete specimens**

## CHAPTER 4

### RESULTS AND DISCUSSION

#### 4.1 GENERAL

In this chapter, results of various non-destructive properties (Ultrasonic pulse velocity, Rebound hammer), mechanical properties (Compressive strength, Flexural strength, Split tensile strength) and durability properties (Rapid chloride permeability, Water absorption, Water permeability, Sorptivity) of various concrete mixes including 100% NAC, 100% RAC and 100% CRAC are discussed. All the tests conducted on the non-destructive, mechanical and durability properties of these concrete mixes were in accordance with the test methods that were reported in Chapter 3.

#### 4.2 TESTS ON NON-DESTRUCTIVE PROPERTIES

##### 4.2.1 Ultrasonic Pulse Velocity Test

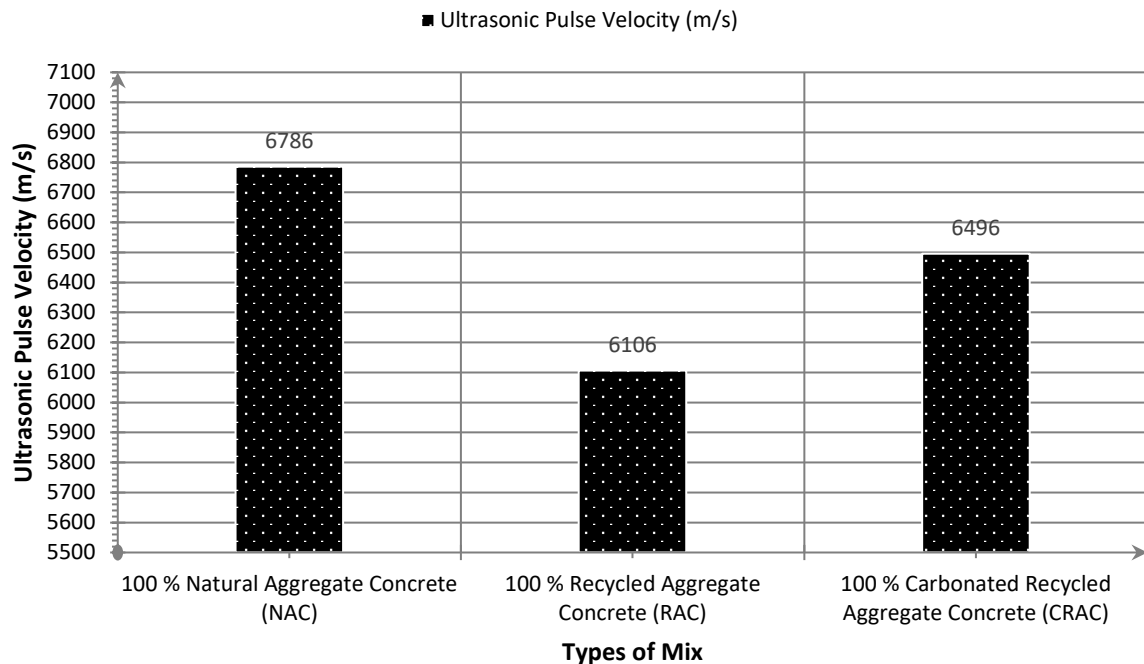
For each type of concrete mix, three concrete cubes of size 150×150×150 mm were casted and 28 days curing of specimens was done for determining the UPV values of various concrete mixes including 100% NAC, 100% RAC and 100% CRAC. The UPV values of various concrete mixes at 28 days is shown in Table 4.1. In the form of bar graph, the data is presented in Figure 4.1.

**Table 4.1: UPV values for all types of mix at 28 days**

S.No.	Types of Mix	UPV (m/s) for 28 Days
1.	100 % Natural Aggregate Concrete (NAC)	6786
2.	100 % Recycled Aggregate Concrete (RAC)	6106
3.	100 % Carbonated Recycled Aggregate Concrete (CRAC)	6496

From the Figure 4.1, it is observed that at the 28 days, the UPV value of the 100% RAC shows a decrease of 10.02% as compared to the 100% NAC. This decrease in UPV value may be due to the poor quality of aggregates and formation of micro cracks in the concrete transition zone of RCAs during its crushing process. Also, as compared to NAs, the RCAs had high porosity

and low density. Also, due to high water absorption, the pore spaces in the 100% RAC is more than other concrete mixes, which affects the transmission of ultrasonic waves.



**Figure 4.1: Shows the UPV values for all types of the mix at 28 days**

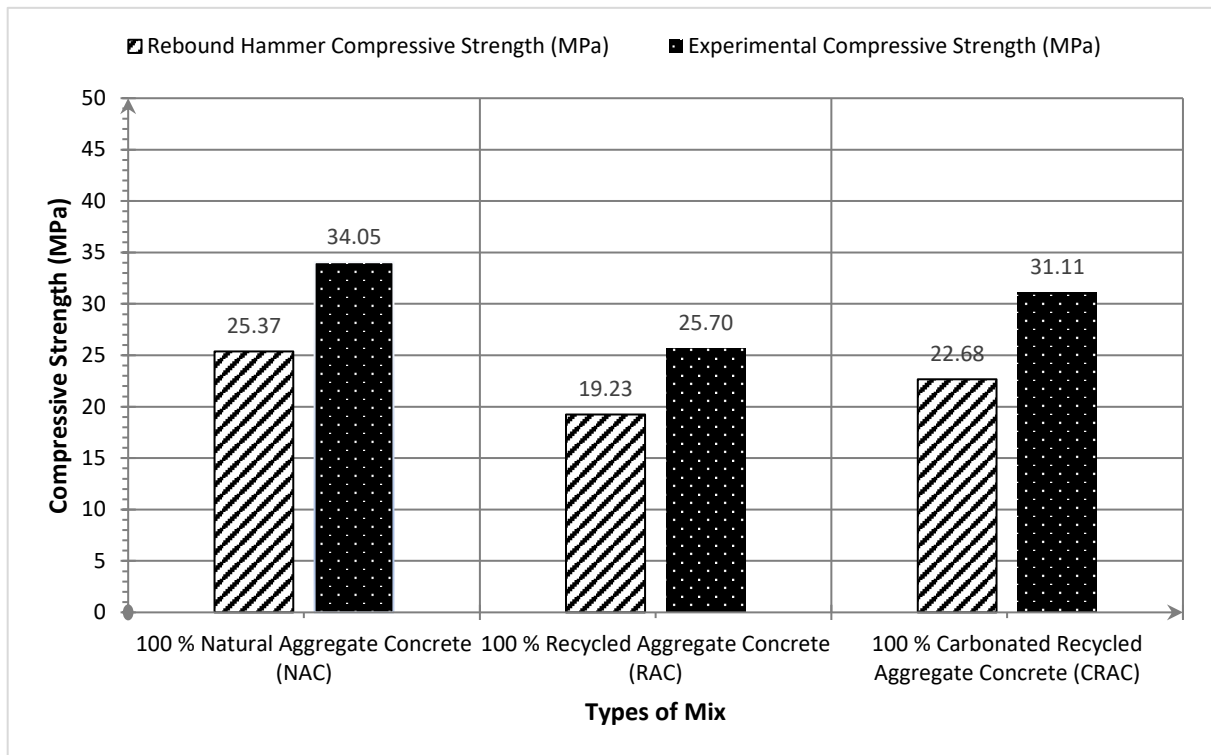
In these results for all types of concrete mix, the UPV values exceeded 4500 m/s and hence the quality of these concretes can be graded as excellent as per IS 13311 (Part 1) : 1992. It is also observed that the UPV value of RAC increases when using the carbonated RCAs. At the 28 days, the UPV value of the 100% CRAC shows an increase of 6.38% as compared to the 100% RAC, but it shows a decrease of 4.27% as compared to the 100% NAC. In attached cement mortar, the two cement hydration products present C-S-H gel and  $\text{Ca}(\text{OH})_2$  reacts with  $\text{CO}_2$  to form  $\text{CaCO}_3$  during carbonation of RCAs, this  $\text{CaCO}_3$  precipitates in pore space of attached cement mortar, hence it densified the RCAs and also, an interfacial transition zone (ITZ) is improved by carbonation of RCAs. After the carbonation of RCAs, the porosity and water absorption of concrete becomes low, which results in fewer pore spaces and hence results in the good transmission of ultrasonic waves.

#### **4.2.2 Rebound Hammer Test**

For each type of concrete mix, three concrete cubes of size  $150 \times 150 \times 150$  mm were cast and 28 days curing of specimens was done for determining the compressive strength by rebound hammer test of various concrete mixes including 100% NAC, 100% RAC and 100% CRAC. The compressive strength by rebound hammer test of various concrete mixes at 28 days is shown in Table 4.2. In the form of bar graph, the data is presented in Figure 4.2.

**Table 4.2: Comparing the Rebound Hammer and Experimental Compressive Strengths for all types of the mix at 28 days**

S.No.	Types of Mix	Rebound Hammer Compressive Strength (MPa) for 28 Days	Experimental Compressive Strength (MPa) for 28 Days
1.	100 % Natural Aggregate Concrete (NAC)	25.37	34.05
2.	100 % Recycled Aggregate Concrete (RAC)	19.23	25.70
3.	100 % Carbonated Recycled Aggregate Concrete (CRAC)	22.68	31.11



**Figure 4.2: Shows the comparison of Rebound Hammer and Experimental Compressive Strengths for all types of the mix at 28 days**

From the Figure 4.2, it is observed that at the 28 days, the compressive strength by rebound hammer test of the all concrete mixes shows a decrement as compared to the experimental Compressive Strengths. This behaviour shown may be due to the reason that in rebound hammer test, a point load is applied on the specimen as compared to the uniform loading acts in the CTM for calculating the experimental Compressive Strength.

### 4.3 TESTS ON MECHANICAL PROPERTIES

#### 4.3.1 Compressive Strength Test

For each type of concrete mix, three concrete cubes of size 150×150×150 mm were casted and 28 days curing of specimens was done for determining the compressive strength of various concrete mixes including 100% NAC, 100% RAC and 100% CRAC. The compressive strength of various concrete mixes at 28 days is shown in Table 4.3. In the form of bar graph, the data is presented in Figure 4.3.

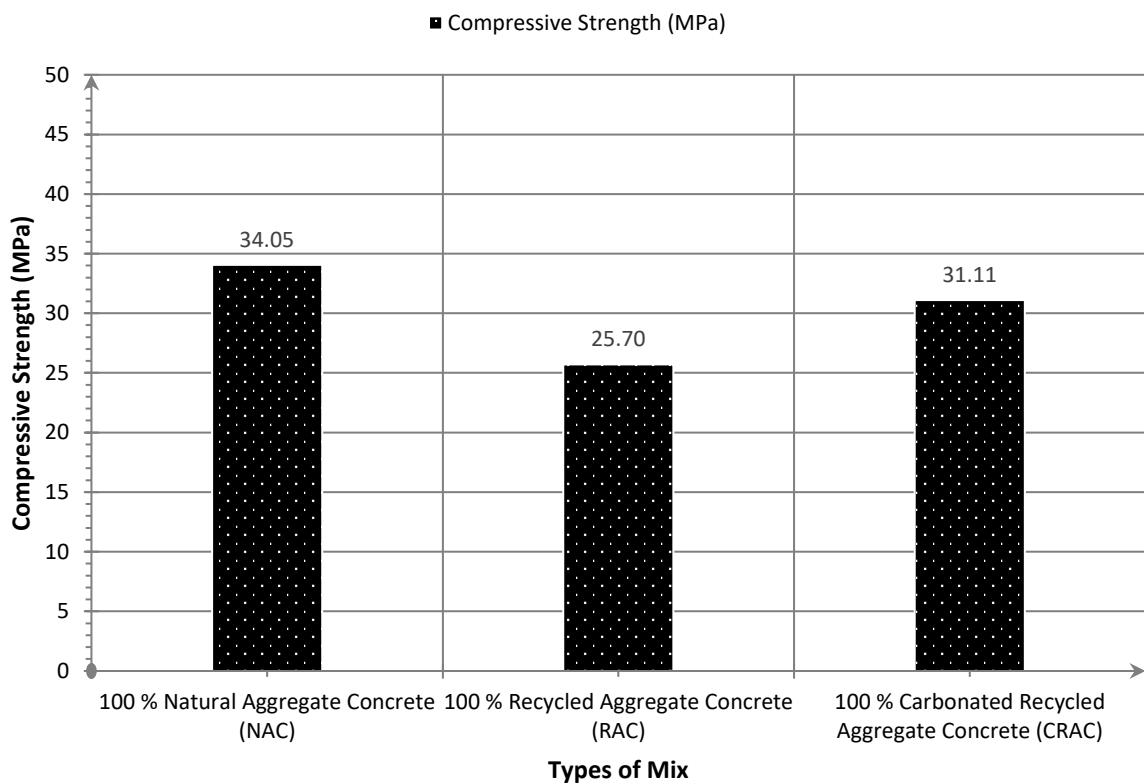
**Table 4.3: Compressive Strength for all types of the mix at 28 days**

S.No.	Types of Mix	Compressive Strength (MPa) for 28 Days
1.	100 % Natural Aggregate Concrete (NAC)	34.05
2.	100 % Recycled Aggregate Concrete (RAC)	25.70
3.	100 % Carbonated Recycled Aggregate Concrete (CRAC)	31.11

From the Figure 4.3, it is observed that at the 28 days, the compressive strength of the 100% RAC shows a decrease of 24.52% as compared to the 100% NAC. This decrease in compressive strength may be due to the poor quality of aggregates and formation of micro cracks in the RCAs during its crushing process. Also, a weak layer of hardened cement paste remains on the surface of RCAs which has high water absorption, so no enough residual water remains in concrete mix to complete the reactions with cement when using the dry RCAs and also, this old adhered mortar weakens the interfacial transition zone (ITZ) in RAC and hence, results in decrease in its compressive strength.

In these results, it is also observed that the compressive strength of RAC increases when using the carbonated RCAs. At the 28 days, the compressive strength of the 100% CRAC shows an increase of 21.05% as compared to the 100% RAC, but it shows a decrease of 8.63% as compared to the 100% NAC. It is found that when the carbonation process is used to treat RCAs, the compressive strength of RAC increases, and it also allows the usage of RCAs at a

higher percentage in new concrete. In attached cement mortar, the two cement hydration products present C-S-H gel and  $\text{Ca}(\text{OH})_2$  reacts with  $\text{CO}_2$  to form  $\text{CaCO}_3$  during carbonation of RCAs, this  $\text{CaCO}_3$  precipitates in pore space of attached cement mortar, hence it densified the RCAs and also, an interfacial transition zone (ITZ) is improved by carbonation of RCAs. Therefore, after carbonation, RCA's water absorption becomes low and hence enough residual water remains in the concrete mix to complete the reactions with cement which results in an increase in its compressive strength.



**Figure 4.3: Shows the Compressive Strength for all types of the mix at 28 days**

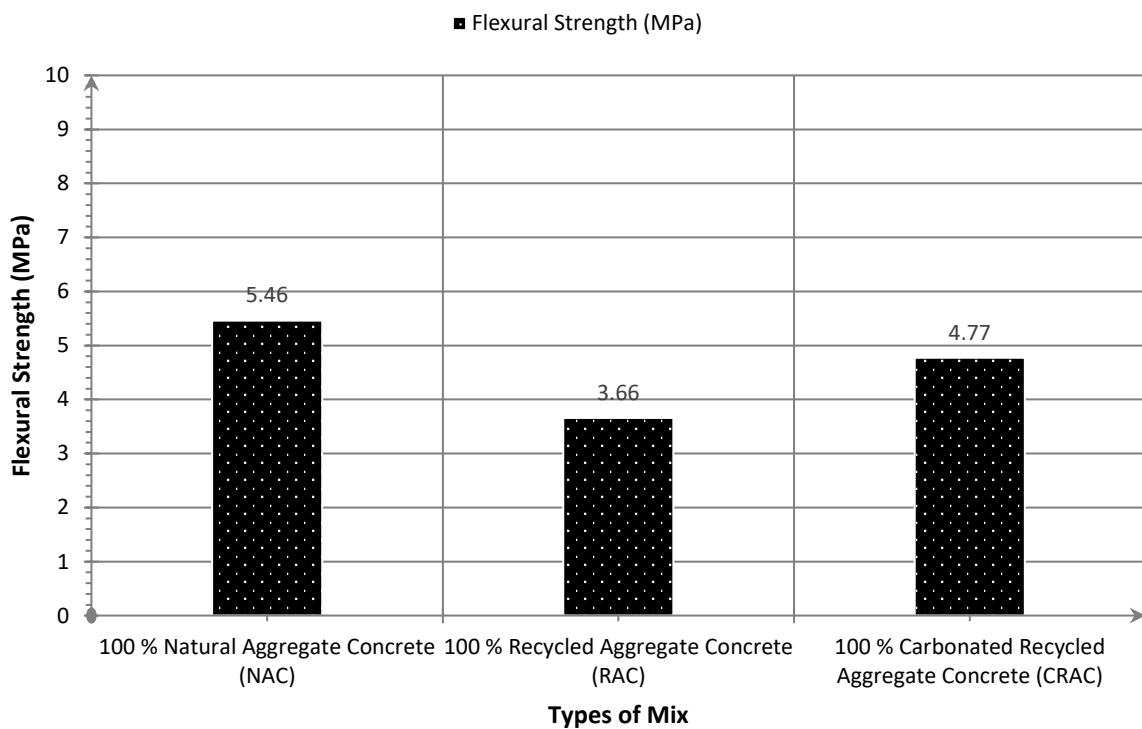
#### 4.3.2 Flexural Strength Test

For each type of concrete mix, three concrete beams of size  $700 \times 150 \times 150$  mm were cast and 28 days curing of specimens was done for determining the flexural strength of various concrete mixes including 100% NAC, 100% RAC and 100% CRAC. The flexural strength of various concrete mixes at 28 days is shown in Table 4.4. In the form of bar graph, the data is presented in Figure 4.4.

**Table 4.4: Flexural Strength for all types of the mix at 28 days**

S.No.	Types of Mix	Flexural Strength (MPa) for 28 Days
1.	100 % Natural Aggregate Concrete (NAC)	5.46
2.	100 % Recycled Aggregate Concrete (RAC)	3.66
3.	100 % Carbonated Recycled Aggregate Concrete (CRAC)	4.77

From the Figure 4.4, it is observed that at the 28 days, the flexural strength of the 100% RAC shows a decrease of 32.96% as compared to the 100% NAC. This decrease in flexural strength may be due to the poor quality of aggregates and formation of micro cracks in the RCAs during its crushing process. Also, due to attached cement mortar presence on the surface of RCA, the surface texture of RCA becomes rough. With an increase in RCA's quantity in concrete, the strength of aggregate-mortar ITZs decreases, therefore it reduces the RAC's flexural strength.



**Figure 4.4: Shows the Flexural Strength for all types of the mix at 28 days**

In these results, it is also observed that the flexural strength of RAC increases when using the carbonated RCAs. At the 28 days, the flexural strength of the 100% CRAC shows an increase of 30.32% as compared to the 100% RAC, but it shows a decrease of 12.63% as compared to the 100% NAC. In attached cement mortar, the two cement hydration products present C-S-H gel and  $\text{Ca}(\text{OH})_2$  reacts with  $\text{CO}_2$  to form  $\text{CaCO}_3$  during carbonation of RCAs, this  $\text{CaCO}_3$  precipitates in pore space of attached cement mortar, hence it densified the RCAs and also, an interfacial transition zone (ITZ) is improved by carbonation of RCAs, which results in an increase in its flexural strength.

### 4.3.3 Split Tensile Strength Test

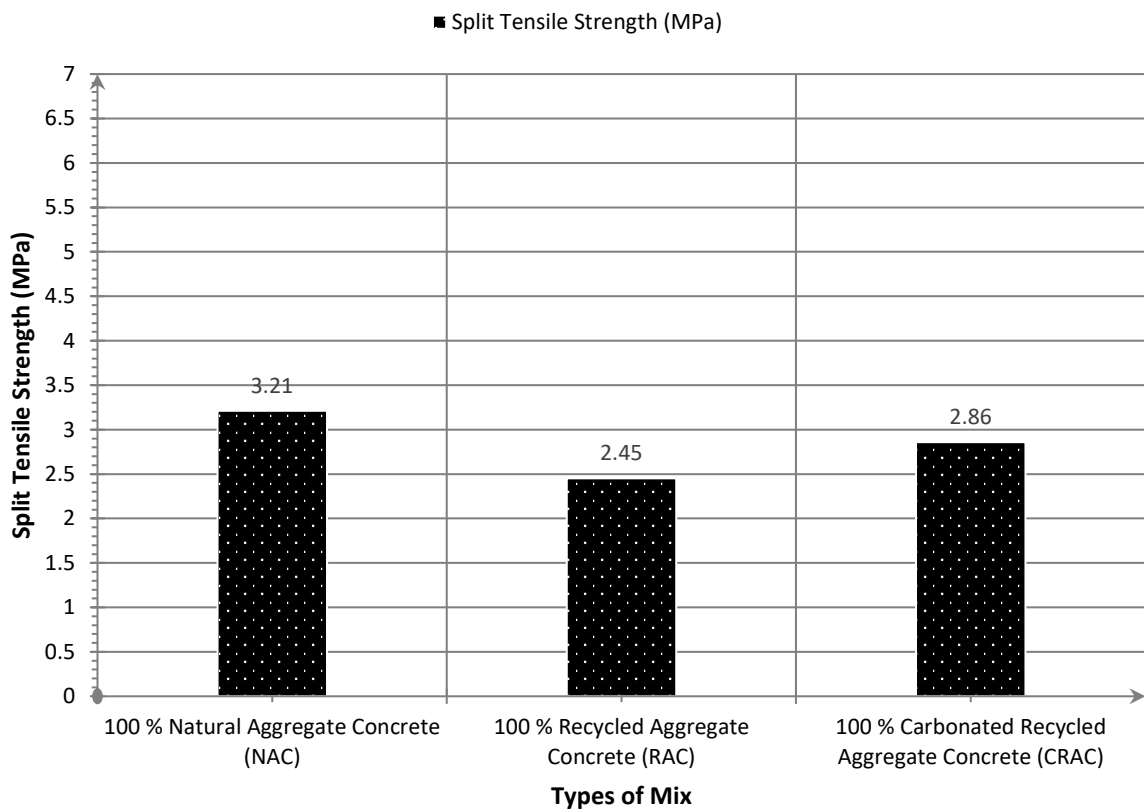
For each type of concrete mix, three concrete cylinders of diameter 100 mm and height 200 mm were cast and 28 days curing of specimens was done for determining the split tensile strength of various concrete mixes including 100% NAC, 100% RAC and 100% CRAC. The split tensile strength of various concrete mixes at 28 days is shown in Table 4.5. In the form of bar graph, the data is presented in Figure 4.5.

**Table 4.5: Split Tensile Strength for all types of the mix at 28 days**

S.No.	Types of Mix	Split Tensile Strength (MPa) for 28 Days
1.	100 % Natural Aggregate Concrete (NAC)	3.21
2.	100 % Recycled Aggregate Concrete (RAC)	2.45
3.	100 % Carbonated Recycled Aggregate Concrete (CRAC)	2.86

From the Figure 4.5, it is observed that at the 28 days, the split tensile strength of the 100% RAC shows a decrease of 23.67% as compared to the 100% NAC. This decrease in split tensile strength may be due to the poor quality of aggregates and formation of micro cracks in the RCAs during its crushing process. Also, due to porous mortar presence on the surface of RCA, therefore at the surface of aggregate the water absorption increases. With an increase in RCA's quantity in concrete, the strength of aggregate-mortar ITZs decreases, therefore it reduces the RAC's split tensile strength.

In these results, it is also observed that the split tensile strength of RAC increases when using the carbonated RCAs. At the 28 days, the split tensile strength of the 100% CRAC shows an increase of 16.73% as compared to the 100% RAC, but it shows a decrease of 10.90% as compared to the 100% NAC. In attached cement mortar, the two cement hydration products present C-S-H gel and  $\text{Ca}(\text{OH})_2$  reacts with  $\text{CO}_2$  to form  $\text{CaCO}_3$  during carbonation of RCAs, this  $\text{CaCO}_3$  precipitates in pore space of attached cement mortar, hence it densified the RCAs and therefore decreases its water absorption and also, an interfacial transition zone (ITZ) is improved by carbonation of RCAs, which results in an increase in its split tensile strength.



**Figure 4.5: Shows the Split Tensile Strength for all types of the mix at 28 days**

#### 4.4 TESTS ON DURABILITY PROPERTIES

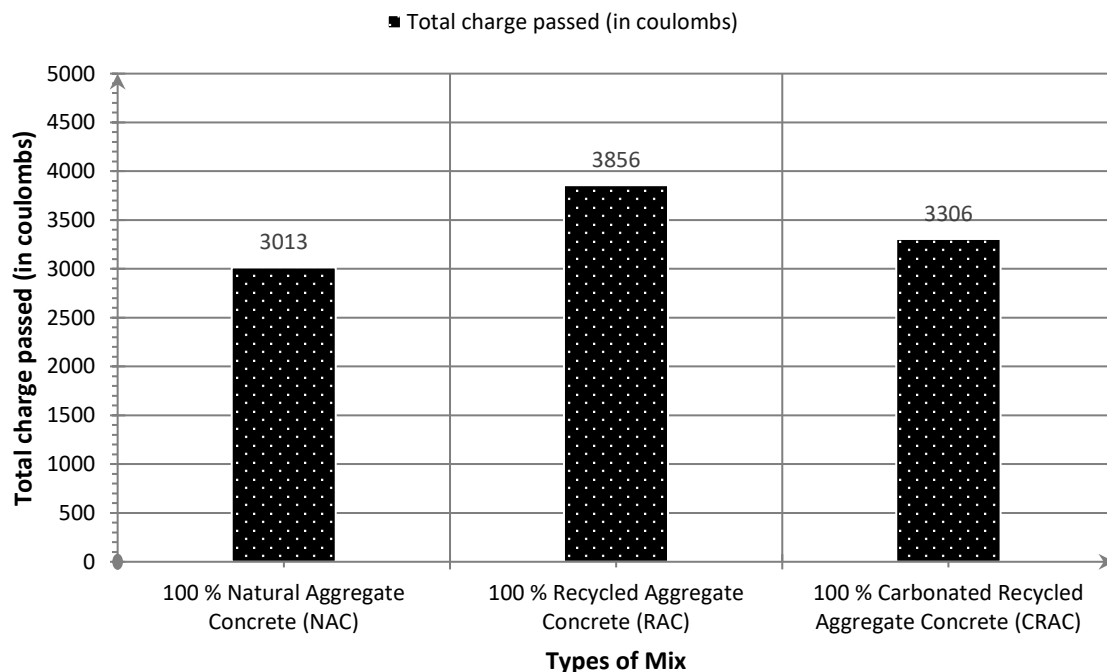
##### 4.4.1 Rapid Chloride Permeability test

For each type of concrete mix, a concrete cylinder of diameter 100 mm and height 200 mm was cast and 28 days curing of specimens was done for determining the rapid chloride permeability of various concrete mixes including 100% NAC, 100% RAC and 100% CRAC. It was cut into slices of diameter 100 mm and height 50 mm to prepare samples for this test. The rapid chloride permeability of various concrete mixes at 28 days is shown in Table 4.6. In the form of bar graph, the data is presented in Figure 4.6.

**Table 4.6: Total charge passed (in coulombs) for all types of the mix at 28 days**

S.No.	Types of Mix	Total charge passed (in coulombs) at 28 Days	Permeability as per ASTM C1202 - 12
1.	100 % Natural Aggregate Concrete (NAC)	3013	Moderate
2.	100 % Recycled Aggregate Concrete (RAC)	3856	Moderate
3.	100 % Carbonated Recycled Aggregate Concrete (CRAC)	3306	Moderate

From the Figure 4.6, it is observed that at the 28 days, the chloride-ion penetration of the 100% RAC shows an increase of 27.97% as compared to the 100% NAC. This increase in chloride-ion penetration may be due to the formation of micro cracks at the aggregate-paste interface of RCAs during its crushing process. Also, due to porous mortar presence on the surface of RCA, therefore at the surface of aggregate the water absorption increases.



**Figure 4.6: Shows the Total charge passed (in coulombs) for all types of the mix at 28 days**

In these results, it is also observed that the chloride-ion penetration of RAC decreases when using the carbonated RCAs. At the 28 days, the chloride-ion penetration of the 100% CRAC

shows a decrease of 14.26% as compared to the 100% RAC, but it shows an increase of 9.72% as compared to the 100% NAC. In attached cement mortar, the two cement hydration products present C-S-H gel and  $\text{Ca(OH)}_2$  reacts with  $\text{CO}_2$  to form  $\text{CaCO}_3$  during carbonation of RCAs, this  $\text{CaCO}_3$  precipitates in pore space of attached cement mortar, hence it densified the RCAs and therefore decreases its water absorption which results in decrease in the chloride-ion penetration.

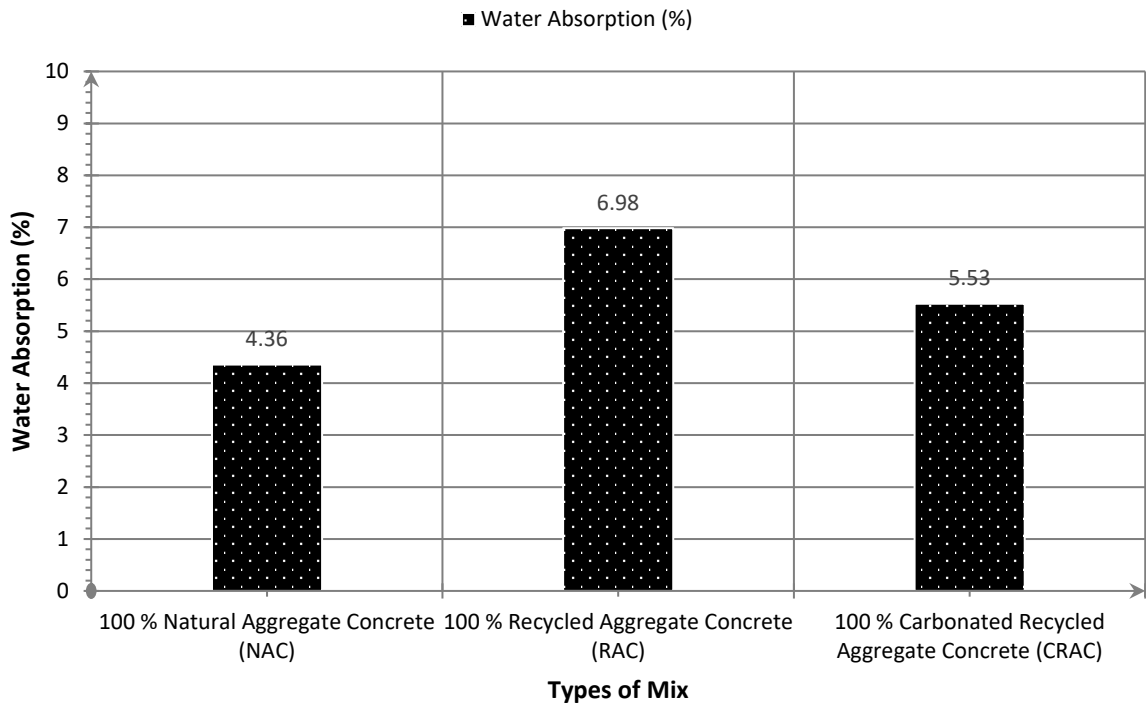
#### 4.4.2 Water Absorption Test

For each type of concrete mix, three concrete cubes of size 150×150×150 mm were cast and 28 days curing of specimens was done for determining the water absorption of various concrete mixes including 100% NAC, 100% RAC and 100% CRAC. The water absorption of various concrete mixes at 28 days is shown in Table 4.7. In the form of bar graph, the data is presented in Figure 4.7.

**Table 4.7: Water Absorption (%) for all types of the mix at 28 days**

S.No.	Types of Mix	Water Absorption (%) at 28 Days
1.	100 % Natural Aggregate Concrete (NAC)	4.36
2.	100 % Recycled Aggregate Concrete (RAC)	6.98
3.	100 % Carbonated Recycled Aggregate Concrete (CRAC)	5.53

From the Figure 4.7, it is observed that at the 28 days, the water absorption of the 100% RAC shows an increase of 60.09% as compared to the 100% NAC. This increase in water absorption may be due to the poor quality of aggregates and formation of micro cracks at the aggregate-paste interface of RCAs during its crushing process. Also, due to porous mortar presence on the surface of RCA, therefore at the surface of aggregate the water absorption increases.



**Figure 4.7: Shows the Water Absorption (%) for all types of the mix at 28 days**

In these results, it is also observed that the water absorption of RAC decreases when using the carbonated RCAs. At the 28 days, the water absorption of the 100% CRAC shows a decrease of 20.77% as compared to the 100% RAC, but it shows an increase of 26.83% as compared to the 100% NAC. In attached cement mortar, the two cement hydration products present C-S-H gel and  $\text{Ca}(\text{OH})_2$  reacts with  $\text{CO}_2$  to form  $\text{CaCO}_3$  during carbonation of RCAs, this  $\text{CaCO}_3$  precipitates in pore space of attached cement mortar, hence it densified the RCAs and therefore decreases its water absorption.

#### 4.4.3 Water Permeability Test

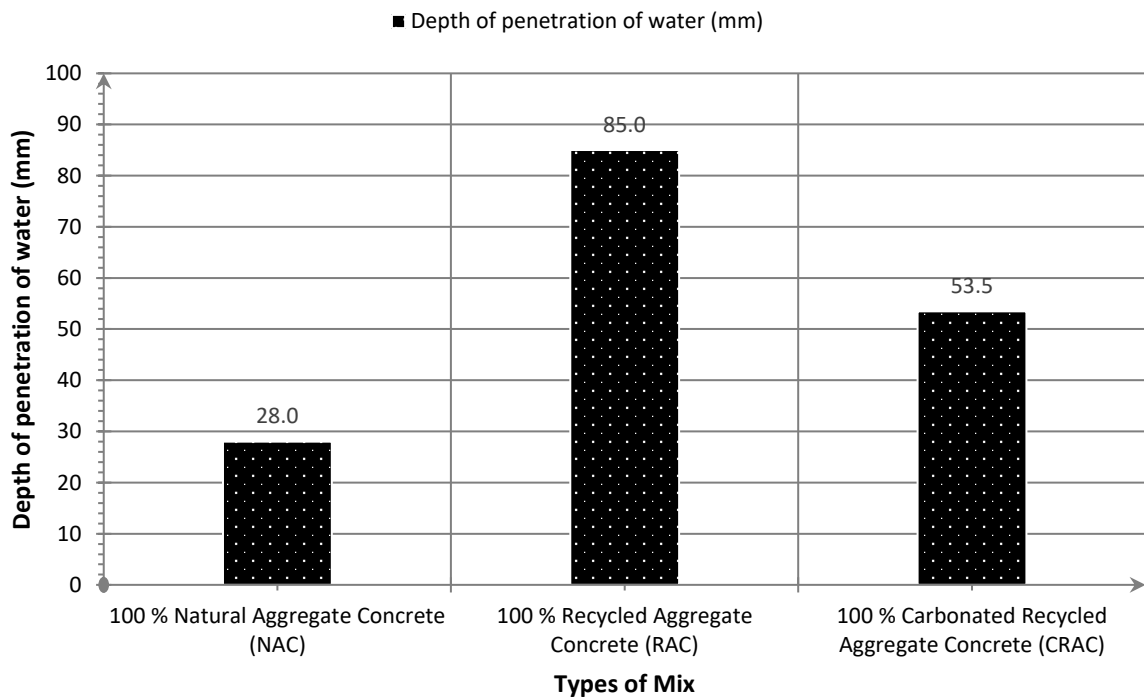
For each type of concrete mix, three concrete cubes of size  $150 \times 150 \times 150$  mm were cast and 28 days curing of specimens was done for determining the water permeability of various concrete mixes including 100% NAC, 100% RAC and 100% CRAC. The depth of penetration of water of various concrete mixes at 28 days is shown in Table 4.8. In the form of bar graph, the data is presented in Figure 4.8.

From the Figure 4.8, it is observed that at the 28 days, the depth of penetration of water of the 100% RAC shows the maximum value of 85.0 mm as compared to the 100% CRAC and 100% NAC which shows the depth of penetration of water of 53.5 mm and 28.0 mm respectively. This increase in depth of penetration of water of 100% RAC may be due to the poor quality of aggregates and formation of micro cracks at the aggregate-paste interface of RCAs during its

crushing process. Also, due to weak and porous mortar presence on the surface of RCA, the porosity of RAC increases which further increases its depth of penetration of water.

**Table 4.8: Depth of penetration of water for all types of the mix at 28 days**

S.No.	Types of Mix	Depth of penetration of water (mm) at 28 Days
1.	100 % Natural Aggregate Concrete (NAC)	28.0
2.	100 % Recycled Aggregate Concrete (RAC)	85.0
3.	100 % Carbonated Recycled Aggregate Concrete (CRAC)	53.5



**Figure 4.8: Shows the Depth of penetration of water for all types of the mix at 28 days**

In these results, it is also observed that the depth of penetration of water of RAC decreases when using the carbonated RCAs. At the 28 days, the depth of penetration of water of the 100% CRAC decreases as compared to the 100% RAC by 31.5 mm, but it shows an increase of 25.5 mm as compared to the 100% NAC. In attached cement mortar, the two cement hydration products present C-S-H gel and  $\text{Ca}(\text{OH})_2$  reacts with  $\text{CO}_2$  to form  $\text{CaCO}_3$  during carbonation of RCAs, this  $\text{CaCO}_3$  precipitates in pore space of attached cement mortar, hence it densified

the RCAs and decreases the porosity of CRAC which further decreases its depth of penetration of water.

#### 4.4.4 Sorptivity Test

For each type of concrete mix, a concrete cylinder of diameter 100 mm and height 200 mm was cast and 28 days curing of specimens was done for determining the sorptivity of various concrete mixes including 100% NAC, 100% RAC and 100% CRAC. It was cut into slices of diameter 100 mm and height 50 mm to prepare samples for this test. The sorptivity of various concrete mixes at 28 days is shown in Table 4.9, Table 4.10 and Table 4.11. In the form of bar graph, the data is presented in Figure 4.9.

**Table 4.9: Sorptivity Test readings for 100% Natural Aggregate Concrete (NAC) at 28**

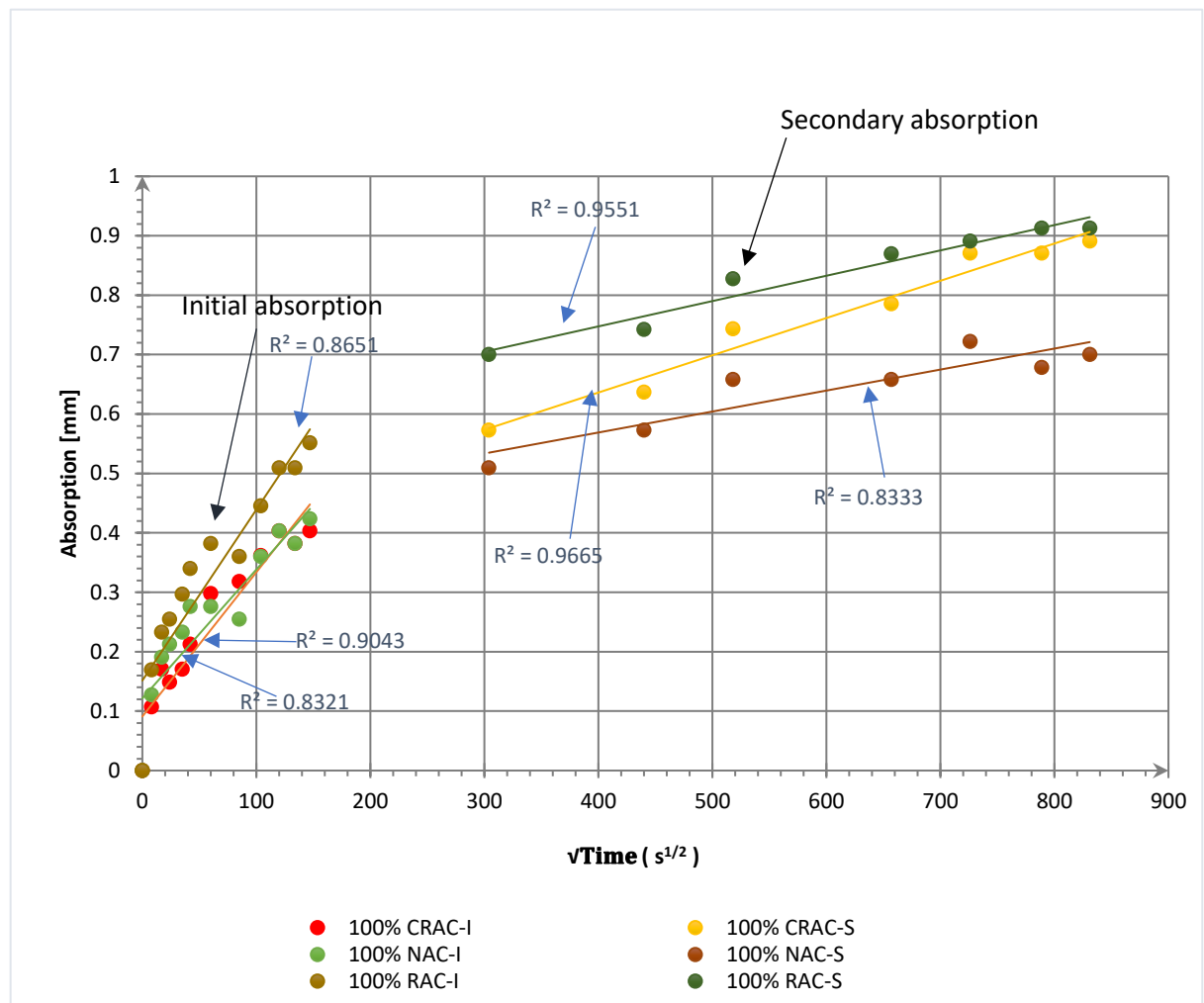
Test Time		$\sqrt{\text{Time}}$ ( $s^{1/2}$ )	Average Mass (g)	Change in Mass (g)	Absorption (mm)
Days	Seconds (s)				
	0	0	963.33	0.00	0.0000
	60	8	964.33	1.00	0.1273
	300	17	964.83	1.50	0.1909
	600	24	965.00	1.67	0.2126
	1200	35	965.16	1.83	0.2330
	1800	42	965.50	2.17	0.2762
	3600	60	965.50	2.17	0.2762
	7200	85	965.33	2.00	0.2546
	10800	104	966.16	2.83	0.3603
	14400	120	966.50	3.17	0.4036
	18000	134	966.33	3.00	0.3819
	21600	147	966.66	3.33	0.4239
1	92220	304	967.33	4.00	0.5092
2	193200	440	967.83	4.50	0.5729
3	268500	518	968.50	5.17	0.6582
5	432000	657	968.50	5.17	0.6582
6	527580	726	969.00	5.67	0.7219
7	622200	789	968.66	5.33	0.6786
8	691200	831	968.83	5.50	0.7002

**Table 4.10: Sorptivity Test readings for 100% Recycled Aggregate Concrete (RAC) at 28 Days**

Test Time		$\sqrt{\text{Time}}$ (s <sup>1/2</sup> )	Average Mass (g)	Change in Mass (g)	Absorption (mm)
Days	Seconds (s)				
	0	0	944.83	0.00	0.0000
	60	8	946.16	1.33	0.1693
	300	17	946.66	1.83	0.2330
	600	24	946.83	2.00	0.2546
	1200	35	947.16	2.33	0.2966
	1800	42	947.50	2.67	0.3399
	3600	60	947.83	3.00	0.3819
	7200	85	947.66	2.83	0.3603
	10800	104	948.33	3.50	0.4456
	14400	120	948.83	4.00	0.5092
	18000	134	948.83	4.00	0.5092
	21600	147	949.16	4.33	0.5513
1	92220	304	950.33	5.50	0.7002
2	193200	440	950.66	5.83	0.7422
3	268500	518	951.33	6.50	0.8276
5	432000	657	951.66	6.83	0.8696
6	527580	726	951.83	7.00	0.8912
7	622200	789	952.00	7.17	0.9129
8	691200	831	952.00	7.17	0.9129

**Table 4.11: Sorptivity Test readings for 100% Carbonated Recycled Aggregate Concrete (CRAC) at 28 Days**

Test Time		$\sqrt{\text{Time}}$ ( $s^{1/2}$ )	Average Mass (g)	Change in Mass (g)	Absorption (mm)
Days	Seconds (s)				
	0	0	984.66	0.00	0.0000
	60	8	985.50	0.84	0.1069
	300	17	986.00	1.34	0.1706
	600	24	985.83	1.17	0.1489
	1200	35	986.00	1.34	0.1706
	1800	42	986.33	1.67	0.2126
	3600	60	987.00	2.34	0.2979
	7200	85	987.16	2.50	0.3183
	10800	104	987.50	2.84	0.3616
	14400	120	987.83	3.17	0.4036
	18000	134	987.66	3.00	0.3819
	21600	147	987.83	3.17	0.4036
1	92220	304	989.16	4.50	0.5729
2	193200	440	989.66	5.00	0.6366
3	268500	518	990.50	5.84	0.7435
5	432000	657	990.83	6.17	0.7855
6	527580	726	991.50	6.84	0.8708
7	622200	789	991.50	6.84	0.8708
8	691200	831	991.66	7.00	0.8912



**Figure 4.9: Shows the Sorptivity Test results for all types of the mix at 28 Days**

From the Figure 4.9, it is observed that at the 28 days, the sorptivity of the 100% RAC shows the maximum value as compared to the 100% CRAC and 100% NAC. This increase in sorptivity of 100% RAC may be due to the poor quality of aggregates and formation of micro cracks at the aggregate-paste interface of RCAs during its crushing process. Also, due to weak and porous mortar presence on the surface of RCA, the porosity of RAC increases which further increases its sorptivity.

In these results, it is also observed that the sorptivity of RAC decreases when using the carbonated RCAs. At the 28 days, the sorptivity of the 100% CRAC decreases as compared to the 100% RAC, but it shows an increase as compared to the 100% NAC. In attached cement mortar, the two cement hydration products present C-S-H gel and  $\text{Ca}(\text{OH})_2$  reacts with  $\text{CO}_2$  to form  $\text{CaCO}_3$  during carbonation of RCAs, this  $\text{CaCO}_3$  precipitates in pore space of attached cement mortar, hence it densified the RCAs and decreases the porosity of CRAC which further decreases its sorptivity.

## CHAPTER 5

### CONCLUSIONS

#### 5.1 GENERAL

In this study to improve the quality of RCAs, an accelerated carbonation technique had been investigated. In this chapter, the main conclusions drawn from the results of various non-destructive properties (Ultrasonic pulse velocity, Rebound hammer), mechanical properties (Compressive strength, Flexural strength, Split tensile strength) and durability properties (Rapid chloride permeability, Water absorption, Water permeability, Sorptivity) of various concrete mixes including 100% NAC, 100% RAC and 100% CRAC are discussed.

#### 5.2 MAIN CONCLUSIONS OF THE STUDY

- At the 28 days, the UPV value of the 100% RAC shows a decrement of 10.02% as compared to the 100% NAC. This is due to the formation of micro-cracks in the concrete transition zone of RCAs during its crushing process and also the pore spaces in the 100% RAC is more than other concrete mixes, which affects the transmission of ultrasonic waves. At the 28 days, the UPV value of the 100% CRAC shows an increment of 6.38% as compared to the 100% RAC, but it shows a decrement of 4.27% as compared to the 100% NAC. Because during carbonation of RCAs, the  $\text{CaCO}_3$  precipitates in pore space of attached cement mortar, hence it densified the RCAs and also after the carbonation of RCAs, the porosity and water absorption of concrete becomes low, which results in less pore spaces and hence results in the good transmission of ultrasonic waves.
- At the 28 days, the compressive strength by rebound hammer test of the all-concrete mixes shows a decrement as compared to the experimental Compressive Strengths. This behaviour shown is due to the reason that in the rebound hammer test, a point load is applied on the specimen as compared to the uniform loading acts in the CTM for calculating the experimental Compressive Strength.
- At the 28 days, the compressive strength of the 100% RAC shows a decrement of 24.52% as compared to the 100% NAC. This is due to the poor quality of aggregates and formation of micro-cracks in the RCAs during its crushing process. Also, a weak layer of hardened cement paste remains on the surface of RCAs which has high water absorption, so no enough residual water remains in the concrete mix to complete the reactions with cement when using the dry RCAs. At the 28 days, the compressive

strength of the 100% CRAC shows an increment of 21.05% as compared to the 100% RAC, but it shows a decrement of 8.63% as compared to the 100% NAC. Because during carbonation of RCAs, the  $\text{CaCO}_3$  precipitates in pore space of attached cement mortar, hence it densified the RCAs and also after carbonation, RCA's water absorption becomes low and hence enough residual water remains in the concrete mix to complete the reactions with cement.

- At the 28 days, the flexural strength of the 100% RAC shows a decrement of 32.96% as compared to the 100% NAC. Because due to the attached cement mortar presence on the surface of RCA, the surface texture of RCA becomes rough. With an increase in RCA's quantity in concrete, the strength of aggregate-mortar ITZs decreases. At the 28 days, the flexural strength of the 100% CRAC shows an increment of 30.32% as compared to the 100% RAC, but it shows a decrement of 12.63% as compared to the 100% NAC. Because during carbonation of RCAs, the  $\text{CaCO}_3$  precipitates in pore space of attached cement mortar, hence it densified the RCAs and also, an interfacial transition zone (ITZ) is improved by carbonation of RCAs.
- At the 28 days, the split tensile strength of the 100% RAC shows a decrement of 23.67% as compared to the 100% NAC. This is due to the poor quality of aggregates and formation of micro cracks in the RCAs during its crushing process and also due to porous mortar presence on the surface of RCA, therefore, at the surface of aggregate the water absorption increases. With an increase in RCA's quantity in concrete, the strength of aggregate-mortar ITZs decreases. At the 28 days, the split tensile strength of the 100% CRAC shows an increment of 16.73% as compared to the 100% RAC, but it shows a decrement of 10.90% as compared to the 100% NAC. Because during carbonation of RCAs, this  $\text{CaCO}_3$  precipitates in pore space of attached cement mortar, hence it densified the RCAs and therefore decreases its water absorption and also, an interfacial transition zone (ITZ) is improved by carbonation of RCAs.
- At the 28 days, the chloride-ion penetration of the 100% RAC shows an increment of 27.97% as compared to the 100% NAC. This is due to the formation of micro-cracks at the aggregate-paste interface of RCAs during its crushing process and also due to porous mortar presence on the surface of RCA, therefore, at the surface of aggregate the water absorption increases. At the 28 days, the chloride-ion penetration of the 100% CRAC shows a decrement of 14.26% as compared to the 100% RAC, but it shows an increment of 9.72% as compared to the 100% NAC. Because during carbonation of

RCA, the  $\text{CaCO}_3$  precipitates in pore space of attached cement mortar, hence it densified the RCA and therefore shows a decrement in its chloride-ion penetration.

- At the 28 days, the water absorption of the 100% RAC shows an increment of 60.09% as compared to the 100% NAC. This is due to the poor quality of aggregates and formation of micro-cracks at the aggregate-paste interface of RCA during its crushing process. Also, due to porous mortar presence on the surface of RCA, therefore at the surface of aggregate the water absorption increases. At the 28 days, the water absorption of the 100% CRAC shows a decrement of 20.77% as compared to the 100% RAC, but it shows an increase of 26.83% as compared to the 100% NAC. Because during carbonation of RCA, the  $\text{CaCO}_3$  precipitates in pore space of attached cement mortar, hence it densified the RCA and therefore shows a decrement in its water absorption.
- At the 28 days, the depth of penetration of water of the 100% RAC shows an increment as compared to the 100% NAC by 57 mm. This increment is due to the poor quality of aggregates and formation of micro-cracks at the aggregate-paste interface of RCA during its crushing process. Also, due to porous mortar presence on the surface of RCA, therefore at the surface of aggregate the depth of penetration of water increases. At the 28 days, the depth of penetration of water of the 100% CRAC shows a decrement as compared to the 100% RAC by 31.5 mm, but it shows an increment of 25.5 mm as compared to the 100% NAC. Because during carbonation of RCA, the  $\text{CaCO}_3$  precipitates in pore space of attached cement mortar, hence it densified the RCA and shows a decrement in the porosity of CRAC which further shows a decrement in its depth of penetration of water.
- At the 28 days, the sorptivity of the 100% RAC shows the maximum value as compared to the 100% CRAC and 100% NAC. This increment in sorptivity of 100% RAC is due to the poor quality of aggregates and formation of micro-cracks at the aggregate-paste interface of RCA during its crushing process. Also, due to weak and porous mortar presence on the surface of RCA, the porosity of RAC shows an increment which further shows an increment in its sorptivity. At the 28 days, the sorptivity of the 100% CRAC shows decrement as compared to the 100% RAC, but it shows an increment as compared to the 100% NAC. Because during carbonation of RCA, the  $\text{CaCO}_3$  precipitates in pore space of attached cement mortar, hence it densified the RCA and shows a decrement in the porosity of CRAC which further shows a decrement in its sorptivity.

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