ENHANCING PHYSICAL PROPERTIES OF RECYCLED AGGREGATES WITH RICE HUSK ASH-CEMENT MIXTURE

Arshiya Benazir Yusuf Kariapper

(138039T)

Dissertation submitted in partial fulfillment of the requirements for the degree Master of Science

full time Reserch-

Department of Earth Resources Engineering

University of Moratuwa

Sri Lanka

September 2016

DECLARATION OF THE CANDIDATE

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(Mrs. A. B. Y. Kariapper)

DECLARATION OF THE SUPERVISORS

The above candidate has carried out research for the Masters dissertation under our supervision.

.... Date:..............................

(Dr. S. Karunarathne, Project Supervisor)

.... Date:..............................

(Dr. D. Nanayakkara, Project Co-Supervisor)

ABSTRACT

Enhancing Physical Properties of Recycled Aggregates with Rice Husk Ash-Cement Mixture

The high water absorption of recycled coarse aggregates (RCA) is a major drawback when it is considered as an alternative material for natural coarse aggregates (NCA). It is mainly due to the porous old attached mortar on the surface of RCA. This study presents an effective method to treat the surface of RCA in order to improve its physical properties. The surface of RCA was coated with slurries that contained varying proportions of rice husk ash (RHA), water and lime or cement. The slurry ratios used in the research varied from 0.625 to 2.00. The solid composition of the slurry was varied as required by varying the RHA to lime or cement composition. The treated recycled coarse aggregate (TRCA) coated with a RHA-lime slurry had been cured for 24 hours and the TRCA coated with RHA-cement slurry had been cured for 3, 7, 14 and 28 days. The water absorption of each scenario was analyzed for the respective curing ages. It was observed that the RHA-lime slurry gives a very weak coating around the surface of RCA than that given when RHA-cement slurry is used to coat RCA. Therefore RHA-cement slurry is recommended to treat RCA. When analyzing the results it could be seen that with the increase of RHA present in the slurry the water absorption of the TRCA increases and when the slurry gets thinner the water absorption of TRCA achieves a minimum and as the slurry gets even thinner it increases once again. When RCA was coated with slurry containing 100% cement the optimum slurry ratio that gave the minimum water absorption of TRCA was 1.500 and when a mixture of RHA and cement was used in the slurry the optimum slurry ratio that gave the minimum water absorption of TRCA was 0.875. In most scenarios the highest reduction in the water absorption of TRCA was achieved at a curing age of 7 days. A grade 30 concrete was made with three selected scenarios of TRCA coated with the RHA-cement slurry, RCA and NCA. The concrete scenarios made with the TRCA and NCA obtained strengths greater than 30 N/mm^2 after 28 days of curing, except that made with RCA. The proposed treatment method can be used to reduce the water absorption of RCA from 6.01% to 3.53-4.44 %. Furthermore when RCA is treated by using this treatment method the negative impact RCA has on the fresh and hardened concrete properties can also be negated.

Keywords: Recycled coarse aggregates (RCA), treated recycled coarse aggregates (TRCA), Rice husk ash (RHA), slurry ratio, cement

DEDICATION

I dedicate this book to my husband for being there with me from the beginning of this adventure till the end, for listening to all my hues and cries, for being ever so patient to my rapidly changing mood swings and for being the most effective but unofficial team player in this study.

I would also like to dedicate this book to my mother for her endless support and baking given to me.

ACKNOWLEDGEMENT

I would first like to express my sincere gratitude to my research supervisors Dr. S. Karunarathne (main supervisor) and Dr. (Mrs) D. Nanayakkara (Co-supevisor) for their immense support, patience, guidance, expertise knowledge and motivation given to me during my MSc. study and related research. Without their backing and motivation this research and dissertation would have remained a dream. I am ever so grateful for the opportunity that I was bestowed upon and ever so thankful to have been given the opportunity to work with my research supervisors who were my advisors, mentors and beacon of light throughout my MSc. study.

I am deeply grateful to Prof. S.M.A. Nanayakkara who was the chief examiner in the progress review of this study. The expertise knowledge, advice and insightful comments he shared with me and his guidance and encouragement given to me and most importantly the questions aroused in every progress review helped me to stir this ship on to safe waters. Furthermore I am ever so grateful to him who was the former head of Department of Civil Engineering for providing all necessary lab facilities and transportation facilities needed to carry out this tedious task.

I would like to thank Dr. H. M. R. Premasiri who was the former post graduate research coordinator of the Department of Earth Resources Engineering and Prof. N. P. Ratnayake who is the post graduate research coordinator of the Department of Earth Resources Engineering for guiding me to my goals and making sure I fulfilled all my dead lines on time.

I would like to show my gratitude to Dr. A. M. K. B. Abeysinghe who was the former head of the Department of Earth Resources Engineering and Dr. H. M. R. Premasiri who is the head of the Department of Earth Resources Engineering for providing all necessary lab facilities needed to carry out this research study.

I would like to thank the SRC grants (No.SRC/LT/2013/04) of the University of Morotuwa for financially supporting this study, without their support this research would have remained a fantasy.

My heartiest thanks go to Mr. Leenas Perera who is the lab attendant of the material testing laboratory of the Department of Civil Engineering, for providing me with all the support, necessary instruments and knowledge throughout my research project. The support given by him helped me to reduce the weight placed on my shoulders and made this research a very easy and enjoyable experience.

I would further like to extend my gratitude to the technical staff of the material testing laboratory and the structural testing laboratory of the Department of Civil Engineering, for all their support given to me with testing and providing me with necessary documentations and codes.

I would further like to extend my gratitude to Mrs. T. Pathiraja who is the analytical chemist and Mrs. M.W.P Sandamali who is the technical officer of the Department of Erath Resources Engineering for their immense support given to me during the research period. I would further like to extend my appreciation to Mr. W.W.S. Perera who is the technical officer of the Department of Earth Resources Engineering for providing me with the necessary instruments and support needed throughout this research.

I am ever so thankful to Eng. D. Dissanayake who is the engineer at the Galle municipal council and Mr. K. Priyankara who is the centre manager of Construction Waste Management in Sri Lanka (COWAM) situated in Galle for providing me with recycled coarse aggregates for free of charge.

I owe my deepest gratitude to the proprietor of ‘Chandani rice mill’ for providing me with rice husk ash needed for this research.

I would like to thank my husband for supporting me physically as well as mentally and for being with me throughout this period and for motivating me during tough and emotional times that I faced during this research study. The research and writing of this dissertation would not have been possible unless for the support and motivation given to me by my husband, mother and my family, for that I am ever so grateful.

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LIST OF ABBREVIATIONS

COWAM: Construction Waste Management in Sri Lanka

NCA: Natural coarse aggregates

RCA: Recycled coarse aggregates

RHA: Rice husk ash

TRCA: Treated recycled coarse aggregates

Chapter 01:INTRODUCTION

The construction industry in the world is expanding by leaps and bounds. With the advancement in science and technology, fast, easier and economical construction methodologies are been used in the industry. Every day scientists and engineers carry out research all around the world to bring about novel and pioneering ideas to create master pieces that sky rocket to the heavens with less human labour and more labour from artificial intelligence. In an era where machines are the leading work force in the construction industry, it is made easy for architects and engineers to exert their knowledge to the maximum gear and create massive awe striking structures that stand erect and strong on the earth.

There was a time where when you opened a window or took a walk down the road, you will be met with a welcoming breeze and a serene environment of trees swaying and the fragrancy of fresh flowers and grass flowing all around and the only sound will be the music orchestrated by nature and the laughter of children playing. Those who lived in an era where machines were unknown this picturesque site today will remain in their minds as a faint memory. Today we are welcomed by the hot smoke and mechanical smells of vehicles smoking like chimneys and tall buildings that stand still and rigid, where the sound of nature is engulfed by the noise of machines. Instead of planting trees the modern world plants concrete structures.

The population of a nation expands with time but the land space on earth remains the same or in some cases depletes due to natural phenomenon like sea erosion, earth quakes, landslides and the list goes on. Once considered massive structures may not be that alluring with time since the needs of people change. Land was not an issue in the past but now land has become a luxury item. With new designs been brought about by architects and engineers, housing projects of a common man to business offices of business tycoons are been made with the state of the art technology, where owners can take a walk in to an unmade building by stepping into a world of virtual reality. It is so easy to spot the difference between old and new concrete structures, but with time the latest concrete structures will become the model of the past and it is exciting to see what it would evolve to be in the future. Old buildings are brought down to the ground to build more economical and energy efficient buildings that can house a large number of people in it. With the demolition of old structures and the construction of new structures a massive amount of waste is generated. It is known as construction and demolition waste.

The world today is facing a huge problem in disposing the construction and demolition waste. In the past dumping any type of waste in land fill areas was common but now since land has become scarce, running out of land fill areas has become the biggest question we all face. Furthermore the construction industry is the largest consumer of mined virgin aggregates in the world. There is a huge environmental impact caused on the environment due to mining of natural aggregates. There was a time where the environment didn’t complain about the atrocities it faced due to the selfish acts of mankind but now we see that the environment is violently retaliating against the humankind. The rate of natural disasters causing catastrophic destruction for man has rapidly increased. As an example rain was considered a blessing but now a day if it rains there are massive floods that flow over the roofs of houses and if it seizes it seizes until the earth cracks like the lips of man due to lack of water. It is now that man realizes that money cannot be eaten and the large concrete trees will not protect them from the fury of nature. Hence the large hue and cry for a sustainable development and green and eco-friendly concepts were brought about by the leading rulers of the world. The “3R” concept that is reduce, reuse and recycle were the foundation of all fields of development.

Rules and regulations were brought about by governments to reduce the amount of construction and demolition waste been disposed in land fill areas. Huge taxes were imposed on contractors that dumped their construction and demolition waste in land fill sites hence reducing the amount been dumped. Recycling of construction and demolition waste was encouraged by the government of many countries and thereby reusing the resultant material obtained by the process hence reducing the natural resources been mined. Selective demolition is carried out by many contractors to recover valuable materials in a structure that can be reused like floor tiles, roof tiles, wood, windows, glass, plastic, wires, pipes and many more before the demolition of the concrete structure. The remnant of the structure is then demolished and the debris obtained is known as demolition waste where a high percentage is of concrete. Construction waste contains the similar constituents as demolition waste but is created with the construction of a building. In many countries the construction and demolition waste is processed by mobile crushers or stationary crushers. Here iron from reinforcement, other pollutants such as plastic, paper, cardboard and many more, major constituents of concrete such as coarse aggregates and fine aggregates are recovered from the construction and demolition concrete waste.

1.1. Recycled Coarse Aggregates (RCA)

The coarse aggregates obtained from the processed construction and demolition waste is known as recycled coarse aggregates (RCA). Due to the significant increase in the demand for construction aggregates the use of alternative material has become very alluring to most. The use of RCA as an alternative material for natural coarse aggregates (NCA) in concrete production is a concept that many researchers and engineers are very interested in. there is a huge load felt on land fill sites due to the increase in the production of waste in the globe and the reduction in primary land that can be used as land fill areas.

RCA can be obtained mainly from concrete, used brick and stones, demolished road materials, blast furnace or steel furnace slag and in some special cases even from glass. There are many application of RCA. It is used as a fill material for reclamation sites, roads, ruts, pathways and many more.

In some countries where natural resources are very scarce and their only option is to import construction aggregates the use of RCA has become very inviting. For example in Singapore witch is an island city the use of RCA has become a very economical substitute for NCA since construction aggregates are imported at a very high price from their neighboring country Malaysia. Furthermore due to the scarcity of land that can be used as waste dump sites the use of RCA has become a very good solution for the large amount of construction and demolition waste been produced in Singapore. The European Union has imposed large taxes on the disposal of construction and demolition waste in land fill areas hence promoting recycling of construction and demolition waste.

Due to natural disasters massive amounts of concrete debris is generated. In the year 2004 South East Asia was left devastated by the massive waves that came roaring in to the lands wiping away all that it could reach. The tsunami that was generated in the Indian Ocean in the year 2004 was one of the most deadliest waves that left many traumatized. The infrastructure of all countries that were victims to these massive waves was sent in to smithereens. There was a large amount of concrete debris generated and the most alluring solution for it was to recycle the concrete debris. For example the Construction Waste Management in Sri Lanka (COWAM project) was initiated by the ZEBAU GmbH, Hamburg to recycle the concrete debris and to produce RCA and recycled sand from it. It was led by TuTech Innovation GmbH, Hamburg it was a project within the framework of the EU ASIA PRO ECO II B Post-Tsunami program. Japan faces many natural disasters due to its geographical placement on earth furthermore its infrastructure is rapidly evolving to touch the skies hence there is a lot of construction and demolition waste been generated. Japan been a very small country wasting space for land fill areas is not a wise solution hence recycling of construction and demolition waste and reusing it has become very inviting.

In many countries such as Singapore, Japan, Russia, the European Union and many more use RCA in structural concrete. The major draw backs faced when using RCA in concrete production is mainly due to the attached mortar on the surface of the RCA. The amount of attached mortar mainly depends upon the parent concrete of the RCA and the crushing process used to obtain the RCA. When the water-cement ratio reduces the cement present in the mortar increases and the water added to the concrete mix reduces hence the concrete gets a higher strength. RCA obtained from parent concrete that had high strengths will contain more attached mortar on the surface of it. On the contrary construction and demolition waste that undergoes a good crushing process will produce RCA with less adhered mortar on its surface. The adhered mortar on the surface of the RCA is very porous hence RCA has a very high water absorption capacity than NCA. When considering the abrasion resistance and impact resistance of RCA it is very low comparing that of NCA. It too is mainly due to the attached mortar present on the surface of RCA. To use RCA as a good alternative material for NCA the adhered mortar present on the surface of the RCA needs to be removed or it needs to be strengthened by implementing a good surface treatment method.

1.2. Rice Husk Ash (RHA)

Rice is an essential food crop and an important source of calories for many around the world. It is mainly grown in China, South-east Asia, the India subcontinent, and some regions in Africa and South America. During the milling process of paddy rice husk is accumulated as a waste product and is considered as the highest contributor for agricultural waste in rice producing countries. In the world around 600 million tons of paddy is annually harvested, in which 120 million tons is obtained as rice husk during the milling process (Kumar, Mohanta, Kumar & Parkash, 2012). Currently instead of dumping rice husk as waste or burning them, it is utilized as a fuel in boilers for the parboiling process of rice. Rice husk ash is a byproduct of the parboiling process of rice. Large amounts of RHA are generated annually and are imposing severe threats on the environment. It is mainly due to the difficulties that arise when disposing RHA. Handling and transporting rice husk or RHA is a tedious job due to its very low bulk density. It causes detrimental effects to land it’s dumped on, to nearby water bodies and air.

According to recent findings it is reported that RHA contains a high percentage of amorphous silica. This is mainly because the rice plat has an ability where it can absorb silica from the earth and accumulate it in its body. Therefore there is a high amount of silica present in rice husk and in RHA. Hence it can be used as a very good pozzolana. A pozzolan is a siliceous or siliceous and aluminum material where it self-possess little or no cementing property but it will, in a finely divided form and in the presence of moisture chemically react with lime at ordinary temperatures to form compounds possessing cementitious properties (Godwin, Maurice, Akobo & Joseph, 2013). The use of RHA as a pozzolan is gaining more advances due to its ability to produce low cost concrete that is durable and has improved mechanical properties. The use of this agro waste product will also reduce the impact it has on the environment (Rukzon & Chindaprasirt, 2008). The embedded energy in ordinary Portland cement is much greater then RHA hence when RHA is used as a partial replacement for ordinary Portland cement a significant saving of cost and energy can be achieved (Ramasamy, 2011).

Many studies have reported that there are significant improvements in the mechanical and durability properties of concrete produced with partially replacing cement with RHA. It is mainly due to a physical effect and a chemical effect caused by RHA ((Ramezanianpour & Shahnazari, 1989), (Ramasamy, 2011), (Ramezanianpour et al, 2009) and (Mehta, 1992)).

Physical effect

- Filler effect
- The amount of coarse pores are reduced
- A large number of nucleation sites are generated

Chemical effect

It is mainly due to the pozzolanic reaction between the amorphous silica present in RHA and the $Ca(OH)_2$ released during the hydration reaction of cement. This reaction produces calcium silicate hydrates which get deposited in the pores present in the cement paste which helps to create a more dense cement paste. This directly enhances the mechanical properties of concrete and its durability.

Many advantages are reported when RHA is used as a partial replacement of cement in order to produce concrete (Givi, Rashid, Aziz & Salleh, 2010). They are,

- The compressive strength and flexural strength can be increased
- The permeability is reduced
- It will give a greater resistance to chemical attack
- Enhanced durability of concrete
- It will produce a much denser concrete
- It can be used as a good heat insulator for walls of buildings
- Light weight concrete can be produced

1.3. Objectives of the Research Study

To study changes in physical properties of recycled aggregates (RCA) due to surface treatment methods using slurries containing,

- Rice husk ash (RHA) - Lime mixture
- Rice husk ash (RHA) - cement mixture

1.4. Benefits of the Project

The use of RCA in concrete production is questioned by most engineers and contractors due to its inferior properties with comparison to NCA. Our main intention of this research is to enhance the physical properties of RCA by coating its surface with slurry containing water, RHA and lime or cement. In this research we hope to reduce the high ware absorption capacity that RCA has. If this can be achieved then it can be used in the production of concrete. Since after treating if the water demand of RCA has reduced then the slump loss that is observed when using RCA to produce concrete will reduce thereby enhancing the workability of concrete and therewith enhancing its strength. Furthermore by impregnating RHA that has pozzolanic characteristics in to the pores of the adhered mortar of RCA can improve the bond between the old mortar of RCA and the new mortar of the concrete made with it. Hence the use of RCA in concrete production can be made inviting to all those in the construction industry as a good alternative material for NCA.

When considering the cost factor it is very cheap for the contractors to dump the construction and demolition waste in land fill sites. In the long run the dumping of construction and demolition waste in land fill areas can lead to detrimental issues. A massive amount of valuable land gets spoiled due to our negligence and improper management of waste. Soil remediation is immensely costly. In the modern world of construction many harmful chemicals are been used to make economical, easy, faster and stronger concrete. When the concrete debris are disposed in land fill sites the chemicals present in them can leach in to the water table and contaminate the drinking water of all those around the dump site. Making all those who use the ground water very sick. The trees absorb the contaminated water into it and accumulate it in its body the fruits that they bear will also have traces of these contaminants depending on the level of contamination of the water table. Clogging of drains due to the washing away of fine constituent material, plastic, rubber, cardboard and many more light weight material present in the construction and demolition waste can cause flooding and can also create a good breeding ground for mosquitoes. This would lead to many infectious sicknesses in the communities all-around the dump site. Hence when considering the long run the dumping of construction and demolition waste is very costly.

In countries that have huge taxes imposed on the disposal of construction and demolition waste the recycling of construction and demolition waste is very economical. When considering the process of recycling construction and demolition waste many costs are encountered and in some cases the sustainability of the process can be questioned. The transportation of the construction and demolition waste uses a lot of energy and pollutes the environment. Hence mobile crushing plants can be encouraged to be used at the construction or demolition site itself. Stationary crushing plants will produce high quality RCA than mobile crushing plants. It is mainly due to the high number of crushing processes present in a stationary crushing plant. The crushing process of construction and demolition waste also consumes more energy and is costly. With the use of RCA in concrete the demand for natural aggregate will reduce. Hence the amount of natural aggregates been mined can be reduced and thereby the impact caused on the environment can be reduced.

RHA is a byproduct of the parboiling process of rice. There needs to be controlled burning of rice husk to produce good quality RHA. The RHA demonstrates good pozzolanic properties when the silica present in it is in the amorphous form. In Sri Lanka rice husk is generally burnt in an uncontrolled environment this will cause a lot of carbon to be present in it. There will be an initial cost to implement a controlled burning system in to the parboiling process. The RHA produced form the parboiling process is coarse hence to use RHA as a pozzolan it needs to be ground in to very fine particles. The grinding process of RHA will consume energy and hence it will get added in to the cost factor when using RHA to treat RCA.

If the use of environmentally friendly material, the impact caused on the environment and sustainability had a monetary value the use RHA to treat RCA will be very economical.

1.5. Scope of the Project

The use of RCA as an alternative material for NCA in the production of concrete is a topic many researchers, engineers and contractors have mixed opinions on. The porous adhered mortar on the surface of the RCA is the ruling factor that induces detrimental effects on its physical properties. Our main intention of this project is to treat the weak porous adhered mortar on the surface of RCA, in order to improve the physical properties of it. The impregnation of fine particles in to the pores of the adhered mortar was the main idea in this research. In this research we hope to treat waste by using another waste product, by doing so we can produce a more sustainable green material. RHA is an agricultural byproduct that can be used as a very good pozzolan. Theoretically a pozzolan is a siliceous or siliceous and aluminum material where itself possess little or no cementing property but, it will in a finely divided form and in the presence of moisture chemically react with $Ca(OH)_2$ at ordinary temperatures to form compounds possessing cementitous properties (Godwin et al, 2013). To treat the RCA we propose to use a slurry where the main constituents were water, RHA and lime or cement. By treating the RCA the pore size of the attached mortar is expected to reduce, thereby the water absorption capacity of the treated RCA should reduce. Furthermore when treated RCA is used in the concrete production the bonding strength between the old weak attached mortar of RCA and the new mortar is expected to be improved due to the constituent materials been used to treat it, hence improving the strength factor of concrete made with it. In this study we hope to come up with a good treatment method in order to enhance the physical properties of RCA that will be easy, economical and sustainable.

Chapter 02:LITERATURE REVIEW

2.1. Construction and Demolition Waste

2.1.1. Introduction

We live in an era where science and technology are the treasured jewels of man. Man’s unquenchable thirst for knowledge has won feats that are unimaginable. It is the key for the door that leads to an easy way of life, where work can be done with less sweat been shed, with less muscles been flexed and less time been spent.

With the escalating advancements in science and technology human needs are speeding where wants of people in the past have become basic needs of those existing today. Those who understand the human nature will know that man’s needs will only increase with time. The population in the world is ever growing. The world population is currently growing at a rate of 1.14% per year (worldometers, 2015). According to the United Nations the global population reached a thumping sum of 7 billion in the year 2011 and is expected to reach a whooping sum of 8 billion in the year 2024 (worldometers, 2015).

Due to the increase in advancement of science, the growing needs of man and the rising population of mankind a huge weight is loaded on the resources of the earth. There was a time when man, beast and nature was balanced and was at peace but now it has been threatened. To supply to the un-extinguishable flame of man’s needs the resources of the earth is depleting. The rate of mining natural resources has increased. But little did man know that the key used to make life easy also opens a door of darkness, horror and sorrow where there is a rise in abnormal health disorders, environmental crisis, bizarre climate change and many more phenomena’s that has left mankind dumbfound. Hence a green concept was brought about in the world where sustainable development paves the way for a safer tomorrow for all that exist on earth.

When considering the construction industry it is one of the biggest players who contribute to the depletion of natural resources in the world. Due to the boom in the construction industry we see many structures having all types of shapes and sizes. Due to the increase in population of man and their needs and since land has become a privilege we see that highly populated cities in the world are been converted into concrete forests where instead of planting trees they have planted tall concrete structures.

According to Isaac Newton’s third law of gravity every action has a reaction. Owning land has become a privilege in these modern times due to the dense population in the world today. With the rise in the construction industry old structures that do not satisfy the building regulations or that are not efficiently designed are been demolished where they would be replaced with sate of the art modern structures. New roads, bridges, high ways and many more structures appear in cities, towns and villages where the differences between them are smudged out. Due to old structures been demolished and new structures been constructed heaps of construction and demolition waste are getting collected in urban areas. Concrete debris left after testing them at universities, laboratories and research institutes and rejected concrete from ready mix plants are an addition to the construction and demolition waste debris (Rahal, 2005).

Identifying a proper management and control system for construction and demolition waste has become a huge challenge in the world today.

2.1.2. Source of Construction and Demolition Waste

Construction waste can be divided into three main categories. They are labor, machinery and material. In which construction material has been classified as the most acute, since almost all of it comes from non-renewable resources (Ekanayake & Ofori, 2000). It is said that around 40 % of the waste generated in the world today is due to the construction industry ((Kulatunga, Amaratunga, Haigh & Rameezdeen, 2006), (Nitivattananon & Borongan, 2007)).

It should be further noted that in some case studies construction and demolition waste can be categorized according to the stages of the construction project. The contracting stage, design stage, procurement stage, transportation, material handling, onsite management, operations and residuals are some of the main stages considered in a construction project ((Kulatunga et al, 2006), (Osmain, Glass & Price, 2008) & (Ekanayake & Ofori, 2000)).

The main sources of construction and demolition waste are from commercial buildings, residential buildings and form road construction. When considering commercial and residential buildings the main contributors to construction and demolition waste are due to the processes of construction, renovation or demolition activities. Waste materials that are most frequently obtained from this category of construction and demolition waste are concrete, metals, drywall, wood, roofing and corrugated cardboard. Whereas road construction waste are engendered during road repairs due to complete or partial removal of old pavements, bridges or road macadam. The waste materials obtained from road construction waste are asphalt and Portland cement concrete which oft contains steel reinforcement (Cosper, Hallenbeck & Brenniman, 1993). The largest contributor to construction and demolition waste is concrete rubble.

It should be pointed out that there is a large amount of construction and demolition waste been generated from laboratories, universities, precast concrete plants and research institutions that do a lot of testing and research on various material or a collaboration to identify the best combinations of materials that needs to be used in a structure that would give the best results. Further, rejected concrete from ready mix plants due to delays during placing, high initial slump and over ordering also contribute a large amount to the escalating construction and demolition waste problem in the world today (Rahal, 2005).

Another key factor that plays a large but silent role in catalyzing construction and demolition waste are the decision making personal involved in any stage of a construction project (Mohammed, Deepthi, Tahsin & Monty, 2012). Due to ignorance, attitude and lack of knowledge of individuals from the design stage to the final handing over stage of a structure a lot of waste can be generated. Most of it could be eliminated if proper planning and efficient management of resources was implemented on site.

Natural disasters such as tornadoes, earth quakes, tsunamis and many more plus man-made disasters mainly considered as war are also another force to bring down structures to the ground. Since natural disasters and war are in a rise the mess of debris that is left behind is also on a rise, hence adding some more misery to the ever so escalating amounts of construction and demolition waste (Parekh & Modhera, 2011).

2.1.3. Amount of Construction and Demolition Waste Generated

The Commonwealth Scientific & Industrial Research Organization (CSIRO) has found out that construction and demolition waste contributes up to 40% of waste generated per year. It’s estimated to be around 14 million tons of construction and demolition waste per year (Ghorpade & Sudarsana, 2012).

In the year 2010 the total waste generated in the European Union (EU) was greater than 2.5 billion tons where 27% (i.e. 672 million tons) were from the mining and quarrying operations and 35% (i.e. 860 million tons) were produced by the construction and demolition activities. According to the Figure 2.1, the mining and quarrying sector and construction and demolition activities has produced more waste than any other economic sector in the European Union for the year 2010. From the total waste produced from these two economic sectors 97% was of either soils or mineral waste like dredging spoil, excavated earth, demolition waste, waste rocks, road construction waste, tailings and etc.. According to Figure 2.2, the mineral and solidified waste generated in the European Union is 76% from the total amount of waste produced (Silva, de Brito & Dhir, 2014). According to Limbachiya et al., the generation of construction and demolition waste of Luxemburg and France is 15 and 7 tons per capita respectively. Furthermore the generation of construction and demolition waste in Ireland and Germany is in between 2 to 4 tons per year. The generation of construction and demolition waste in other European Union countries is in between 0.2 tons per year (e.g.: Norway) to 2 tons per year (e.g. United Kingdom). The core construction and demolition waste obtained from civil engineering infrastructure and demolished buildings only, will sum-up to around 180 million tons per capita that is 480kg/person.year in the European Union (Limbachiya, Koulouris, Roberts & Fried, 2004).

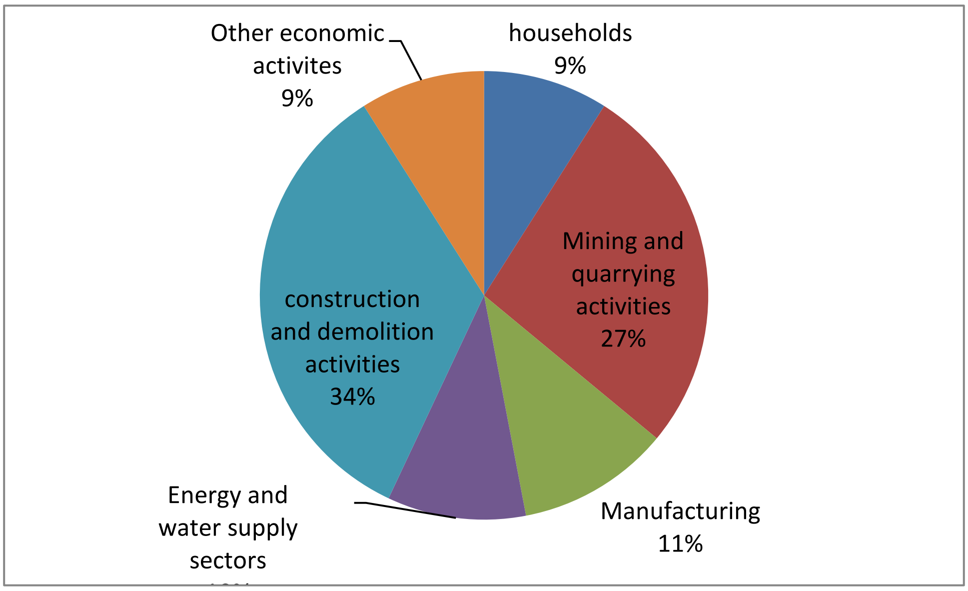


Figure 2. 1: Total Waste Generated in the European Union according to Economic Activities

Source: (Silva, de Brito & Dhir, 2014)

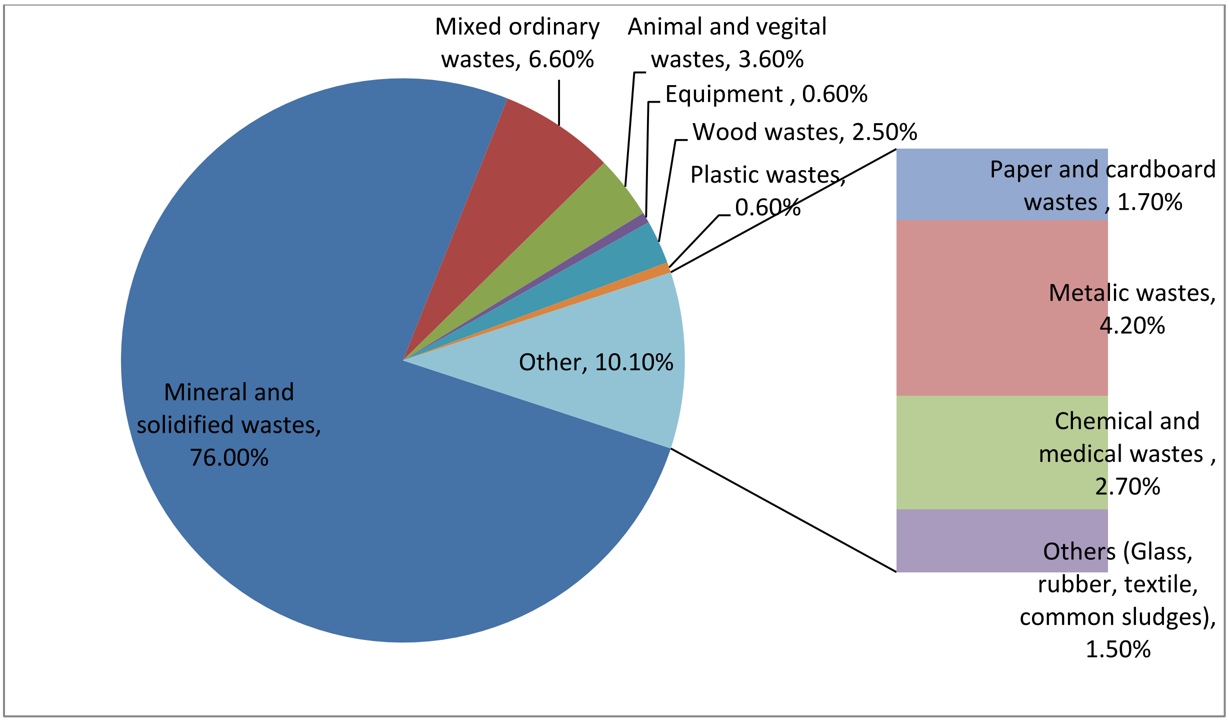


Figure 2. 2: Total Waste Generated in the European Union according to Waste Category

Source: (Silva, de Brito & Dhir, 2014)

The Environmental Protection Agency had estimated that in the United States the generation of waste debris due to construction, renovation of residential and non-residential buildings and demolition summed up to around 170 million tons in the year 2003 (Silva, de Brito & Dhir, 2014).

The waste generated by the construction industry in Brazil is about 41% to 59% of its urban solid waste. This indicates that almost half of the urban solid waste generated in Brazil is from construction and demolition waste (de Medeiros, Fucale, Póvoas & Gusmão, 2009). The production of construction waste in Brazil is internationally estimated to vary in-between 130 to 3000 kg/person.year. In Recife the state capital of Pernambuco the construction and demolition waste is 49% of its urban solid waste and from it only 20% of construction waste is obtained by companies been licensed in public authorities the rest will be illegally dumped in land fill areas (de Medeiros et al, 2009). Ronaldo et al., states that even though 20%

of the state’s construction waste is obtained by authorized companies in the year 2004 only 1 % of construction waste found its way in to licensed solid waste fill areas the remaining 353,606 tons were dumped in illegal areas.

A study conducted by the Council for Scientific and Industrial Research (CSIR) Building and Construction Technology (Boutek) in the year 2004 states that in South Africa approximately a million tons of construction and demolition waste ends up in landfill areas (Limbachiya et al, 2004).

A study conducted by Rahal et al., states that in Kuwait the annual consumption of concrete is around 3.5 million cubic meters. According to a survey conducted by the Environment Public Authority (EPA) in the years 2001 and 2002, had found out that from the total waste disposed at the municipal landfills in Kuwait around 58% was made up of construction and demolition waste from it a significant proportion was concrete and masonry rubble. In Kuwait most local ready mix suppliers due to the inadequate management or type of concrete been supplied reject 1% to 2% of the concrete been produced that is around 110,000 metric tons of concrete (13).

Parekh et al., states that the construction industry in India annually generates around 14.5 metric tons of solid waste. It consists of concrete, masonry, gravel, sand, bricks and bitumen (Parekh & Modhera, 2011). Even in Hong Kong 14 million metric tons of construction and demolition waste is generated annually due to the construction industry (Fong, Yeung & Poon, 2004). When considering Si Lanka the largest buyer in the mining and quarrying sector having a total of 76.45% and in the forest sector having a total of 77.23% is the construction industry (Premasiri, Kariapper, Abeysignhe & Karunaratne, 2013).

According to the data gathered on the amounts of construction and demolition waste been generated in the word, we can see that it depends on the variation of geography and geology of countries and cities and their various building methods, norms and traditions. Furthermore the economic back ground of each city, country, region or continent will also have an impact on the generation of construction and demolition waste.

2.1.4. Impact Caused on the Environment due to Construction and Demolition Waste

Construction and demolition waste can be obtained in any stage of a structure. From its building stages to its last laps before been demolished and brought down to ground. 10% of construction and demolition waste is due to new construction, 40% is due to renovation the remaining 50% is due to demolition

Factories, crusher plants and ready mix plants are the manufacturers of the building blocks of any structure which has to find its way to sites which are situated far away. Transportation of raw materials to the construction sites is one way from many ways to contaminate the pure environment. Dust and fumes engulfing the air and roads scattered with remnants of raw material that escaped the massive tippers since the latch of their backs were not securely fastened and noise of the engines and the honking of these heavy vehicles breaking the serenity of ones habitat is detrimental to the environment.

When the raw materials arrive at the construction site again begins the cycle of dust, waste and noise imposing surplus of stress to the environment. At the end of the day when the structure is completed and the client is satisfied the contractor and his team will pull out from the site that was once their second home. It is a known fact in life when humans create something a mess has to be generated, and the size of the mess will depict the management skills of the individual. That is bigger the mess depicts a less skilled individual who has a very high capability of been wasteful with resources and who has a very low rating when it comes to doing a pristine job even though the end product is remarkable. It is sad to say that after the construction of any type of structure there’s always an equal amount of waste generated that is proportionate to the size of the structure piled up waiting to be transported to legal or sometimes even illegal landfills.

At the end of the designed life span of any civil structure due to failure and deterioration of its strength will impose threats on the safety of the community living near it, therefore leaving no other solution other than demolishing it. Hence the materials used to build the structure and some more will be obtained as waste.

Solitarily these raw materials were very useful but when combined with one another as found in the demolished waste they become useless.

Construction and demolition waste consists of plastic, metal, woods, brick, tiles, concrete and etc... The quantity of each component of construction and demolition waste will vary with the global position of the source. Since various countries, cities, communities have vivid building norms that require different types of building materials to be used. It may be due to economic standard, type of structure, purpose of structure, geology, geography, natural disasters and even ones culture. Hence some Construction and demolition waste may contain a higher amount of wood, glass, metals, bricks or concrete.

In Sri Lanka recovery of timber from construction and demolition waste is 100% and the percentage reused of Calicut roof tiles, ceiling panels, toilet fittings, bricks and Cabok (Laterite brick) are 97%, 79%, 79%, 75% and 97% respectively (COWAM Project, 2011). When it comes to demolished concrete, floor and wall tiles and nonferrous materials such as electrical wire, switch boards, plastic and etc. are not recovered at all. It is mainly because these salvaged materials do not have any market. Hence these materials are dumped in land fill areas never to be seen by any eye.

Not only in Sri Lanka but in most countries in the world dump their construction and demolition waste that has no economic benefit in legal or even illegal landfills. When you take a closer look at these materials we see that to make them to existence a major amount of natural resources were used and most of them are from non-renewable sources.

When considering concrete the main four types of materials used are coarse or crushed aggregates, fine aggregates (sand or natural gravel), Portland cement and waster. It doesn’t take a blink of an eye to notice that other than water all the others are from non-renewable sources. Coarse aggregates are obtained from mining large rock structures. Fine aggregates are obtained from digging or dredging a river, lake sea bed or pit. Portland cement is obtained by mining lime stone, shells, shale, chalk or calcareous rock from the earth and crushing, milling and proportioning them with silica, alumina, iron and gypsum (Shetty, 2013).

Whereas ceramic tiles are made up with a large amount of clay along with different proportions of sand feldspar, quartz and water that undergo crushing, proportioning, high pressure and high temperatures to produce exquisite pieces of art that comes in various shapes and sizes to give that special look to any civil structure.

It is an endless quest to explain each source of non-salvaged construction and demolition waste material but it is evident that they all come from non-renewable sources. The natural resources exploited by man took millions, billions and trillions of years to be made. Hence with the boom in the construction industry and the way of life of mankind the depletion of these natural resources has become very fast. Further it is more alarming to understand that most of these natural resources will only be mined at its pure form and not when it is mixed with other natural resources because then it is labeled as waste and non-marketable. Since who needs second hand goods when there is brand new products in the earth’s crust waiting to be mined that is more economical. It should be highlighted that these natural resource are depleting faster and faster. One should think of the future children and ponder on how they will carry on in life without a drop of natural resources. There want be any development, the future generation will have to scrape at the waste their ancestors left behind. Hence the large hue and cry on sustainable development was brought about in the 1992 Earth Summit in Rio de Janeiro (Limbachiya et al, 2004). Now the idea of sustainable development has become a main guiding principle in the construction industry.

Not only the running out of natural resources that we have to be concerned of but the depletion of landfill areas also has become a huge crisis worldwide. Due to the ever growing population of the world today owning land has become a privilege due to its scarcity. Illegal dumping of waste is a menace in many developing countries. It is very sad to say that most of these landfill areas sometimes even legal landfills are not properly designed and well managed, paving the way to ample opportunities of contaminating the surrounding environment.

Therefore when it comes to the non-salvaged construction and demolition waste there are two major negative impacts that occur. They are the mining of nonrenewable resources and throwing them away after it’s used only once and the depletion of properly managed and designed landfill areas. Hence sustainable development has become the future of the way. The 3 R’s or also known as reduce, reuse and recycle is our ultimate goal that needs to be achieved to make sure that our future generations to come will also be able to exploit the natural resources of this earth.

2.2. Recycled Coarse Aggregates (RCA)

2.2.1. Introduction

Concrete mainly consists of coarse aggregates, fine aggregates, cement and water. In some instances it may consist of various types of admixtures and reinforcement depending on the requirement the concrete has to fulfill. Concrete has been used ever since its discovery made by the ancient civilizations. It is said that the history of concrete and cement begins 5000 years back at the time when the pyramids made by the Egyptians stood erect on the ground as the sky scrapers of today. Back then many magnificent monuments were made by the use of concrete. Even today it’s the same without concrete there want be any structures that shoot up to the sky (Premasiri et al, 2013).

Aggregate used in the production of concrete sums up to 70% to 80% of the total volume of concrete. The aggregate used in the concrete acts as comparatively cheap filler for the cementing material. The aggregates will give the concrete a sufficient mass of particles that would be adequate to resist any action of abrasion, applied loads, deformations, percolation of moisture and weather. Hence it’s evident that it plays a major role when considering the concrete properties. By the use of aggregates in concrete the changes that occur in the volume of concrete due to the setting and hardening process and due to changes in the moisture of the cement paste can be mitigated (Parekh & Modhera, 2011).

There are many detrimental effects due to the high usage of concrete in the construction industry. A large amount of raw materials are consumed for the production of cement and concrete hence to cater for the escalating production of these materials natural resources are depleting ever so fast. For the production, storage and transportation of raw materials and the production, transportation, placement and compaction of concrete consume mega amounts of energy and causes a lot of pollution in the environment. A large amount of old concrete is accumulated around the world today due to the demolition of old concrete structures. Hence there’s a crisis of depletion of land fill areas in many developed and developing countries in the world. Thereby illegal dumping of construction and demolition waste has become a menace in the current society today.

It is evident that we as a human race can’t live without concrete but it is our obligation not to cause any devastating damage to the environment we live in and to leave some natural resources to the future generations to come as well. However one of the most unique attributes of concrete is that the major constituents used to make concrete can be replaced by a wide spectrum of materials obtained as industrial by products or industrial waste products and even that obtained from construction and demolition waste.

Recycled aggregates are composed of crushed, graded inorganic particles that are obtained from processing construction and demolition waste (Parekh & Modhera, 2011). The difference between recycled aggregates and natural aggregates is that recycled aggregates compose of mainly natural aggregate and adhered cement mortar. Due to the adhered mortar recycled aggregates have a high water absorption capacity, a low resistance to abrasion and impact, a low density and in some instance a high sulphate, chloride and alkali content (20). Hence the adhered mortar on the surface of the recycled aggregate is the major drawback when considering the use of recycled aggregates in concrete production.

2.2.2. World Demand for Construction Aggregates

According to a survey carried out by the Freedonia Group the demand in the world for construction aggregates for the year 2008 was a grand value of 24.9 billion metric tons. The world construction aggregate demand was predicted to develop at a rate of 2.9% annually. By a recent survey conducted by this group it was forecasted that the construction aggregate sales in the world is to expand 5.8% annually through the year 2012 to the year 2017. That is in the year 2017 the construction aggregate sales is predicted to be 53.2 billion metric tons (Freedonia Group, 2013).

In the year 2012 China was said to have the world's biggest construction aggregate market. When considering the aggregate demand in the Asia/Pacific market alone China was placed number one, where it accounted for 72% of the total aggregate demand of the Asia/Pacific region (Freedonia Group, 2013). It was further stated by the Freedonia Group that China had nearly accounted for half of the world's aggregate demand. The demand for construction aggregates in China increased more than 11% per annum from the year 2007 to the year 2012. This was highlighted as the fastest rate of increase of the demand for construction aggregates globally. India is the second highest consumer of construction aggregates. Even though India was the second largest consumer of aggregates in the world, in the year 2012 the aggregate sales of China was approximately six times that of India. But between the years 2012 and 2017 the demand growth in India will out run the speeding growth that is seen in China nowadays and in the year 2017 will become the largest aggregate consumer in the world (Freedonia Group, 2013). With the saturation and the maturity of the Chinese market the fluctuating demand growth of construction aggregates that was seen in the past decade is proposed to have a steep decline in the future.

It is mainly because China has large deposits of natural aggregates and a thriving economy plus its construction sector is expanding like wild fire. The consumption of sand and crushed stone in China was greater than three-fourths of all aggregate sales in the year 2012. Due to the escalating need of construction aggregates in China and the environmental impact caused by this, the use of recycled aggregates, alternative aggregates and secondary aggregates has become a present reality in China. China is said to be the largest consumer of these sustainable building materials in the world. When considering the other Asia/Pacific countries the sales of sustainable building materials is indicated by a small piece of the pie of aggregate sales in the world.

According to the Freedonia Group in the years 2007 to 2012 there had been a reduction in the aggregate demand in North America, Eastern Europe and Western Europe due to the recession but it is expected to regain in the coming years and is predicted to increase between 3% - 5% per annum through the year 2017. Since after these regions come out of the financial crunch they are in the construction activities of commercial, public and residential sites will spring right back up and hence will have a higher demand for construction aggregates. It was predicted by the Freedonia Group that the aggregate demand in Eastern Europe and North America will have a rapid growth than Western Europe in the years 2012 to the year 2017. The major countries that would be the leading consumers of construction aggregates in these regions were predicted to be the United States, Spain, Italy and Russia (Freedonia Group, 2013).

The Asia/Pacific region and the Africa/Mideast region will continue to be the leading consumers of construction aggregates due to their above average demand in the future years to come (Freedonia Group, 2013).

More than one-half of the world’s aggregate demand between years 2012 to 2017 is made up by crushed stone. It is mainly due to its many performance features such as strength and durability. Due to the depletion of natural resources of sand and gravel and the detrimental impact caused on the environment the high demand for crushed stone will subside all around the world and many sustainable building materials will capture the market such as, alternative aggregates, recycled aggregates and manufactured sand.

2.2.3. The Need to Use Recycle Aggregates

The use of recycled aggregates obtained from construction and demolition waste has become a need in the world today. It’s mainly because of the abnormally high consumption of natural aggregates and the depletion of landfill areas to dispose construction and demolition waste material (Qiu, Tng & Yang, 2014). Hence using recycled concrete aggregates as an alternative material to natural aggregates contributes to a much sustainable and a green development in the world. Thereby reducing the load applied on the natural aggregate resources that are already facing a huge shortage problem all around the world and the massive degradation in the environmental seen today (Guneyisi, Gesogˇlu, Algın & Yazıcı, 2014). Hence it is evident that due to the need of sustainable development and the limited natural resources in the world the use of recycled aggregates such as crushed concrete and crushed asphalt and industrial byproducts such as blast furnace slag, fly ash and rice husk ash will grow (Parekh & Modhera, 2011).

The use of recycled aggregates is very important to countries with limited natural resources and land space. For example when considering an island city state like Singapore it is a pivotal fact to introduce a sustainable development method to restore waste into resources and to expand the lifespan of landfill areas. Hence natural aggregates are imported at very high prices form neighboring countries. Therefore the Singapore government has studied the need to identify alternative aggregate resources; hence the use of recycled coarse aggregate from construction and demolition waste is a very appealing solution (Qiu et al, 2014).

In many parts of the world new rules and regulations have been brought by government bodies to control and reduce the use of primary aggregates by increasing the use of recycled and secondary aggregates where it is economically, environmentally and technically acceptable (Limbachiya et al, 2004). But there is still a pressing need to implement sustainable construction and demolition waste management systems by bringing about strict legislative and regulatory measures by policy makers all around the world.

In the United Kingdom the use of recycled and secondary concrete aggregate as alternative materials for natural aggregates is encouraged by its government by implementing many policies. Such as to support research and development work, implement landfill taxes, implement extraction taxes and many more (Limbachiya et al, 2004).

The use of recycled aggregates has become a very common practice in Australia, USA, Japan and in many European countries. According to Guneyisi et al, (2014) the production of recycled aggregates in the year 2010 in Netherlands, France, Germany, United Kingdom and USA were approximately 20 mega tons, 17 mega tons, 60 mega tons, 49 mega tons and 10 mega tons respectively (Guneyisi et al, 2014).

Due to the detrimental impact caused on the environment by the extraction of natural coarse aggregates the local authorities in Kuwait banned the production of natural coarse aggregates from local quarries in the year 1997. The coarse aggregates were then imported at a higher cost from neighboring countries such as the United Arab Emirates (UAE). Hence the cost of concrete increased causing the total cost for concrete structure in Kuwait to sky rocket (Rahal, 2005). Thereby the recycling of construction and demolition waste to obtain recycled coarse aggregates to make an economically and environmentally friendly concrete has become very common in Kuwait (Rahal, 2005).

In South Africa construction and demolition waste is processed and is converted into recycled coarse aggregates to be used for various aggregate grades, road materials and fine aggregates (Limbachiya et al, 2004).

Hong Kong is a rapidly developing country and the amount of construction and demolition waste generated in it is also equivalently increasing. In the past before the large hue and cry of sustainable development the inert portion of these materials were used as landfill materials to form land for the development work of Hong Kong (Fong et al, 2004). Due to the resistance been made by the public on sea reclamation many of these projects had been put off. Therefore these materials had to be disposed in precious land fill areas. This was not a good solution for the problem faced by the government of Hong Kong since land was precious in this small country. In the end the most productive method to tackle this crisis was recycling the construction and demolition waste (Fong et al, 2004). In order to obtain valuable reusable resources from construction and demolished waste the government of Hong Kong has opened a pilot construction and demolition materials recycling plant in Tuen Mun (Fong et al, 2004). The government, industries and universities of Hong Kong are conducting continuous research in order to widen the spectrum of use of recycled aggregates.

Sustainable development is known as an environmentally friendly development method where modern and in some cases ancient technologies are used in order to save natural resources and energy been used. Main concepts for sustainable development is implementing the 3R's method of reduce, reuse and recycle. Parekh & Modhera (2011), states that the term sustainable construction materials is improperly used to denote recycled materials due to the fact that in some instances to produce them a large energy is required (Parekh & Modhera, 2011).

2.2.4. The Use of Recycled Aggregates in the World

The use of recycled aggregates dates back to the year 1945 at the end of World War II (Kheder & Al-Windawi, 2005). At that time the horrific war had left an immense destruction and devastation to all living beings on earth. To rebuild the structures that were destroyed by the war a large amount of construction aggregates were needed. It was very economical at that time to reuse the construction and demolition waste to rebuild the fallen concrete structures (Kheder & Al-Windawi, 2005).

In Australia recycled aggregates are a very common alternative material that is used to replace natural aggregates for concrete production. In the Australian market around five million tons of masonry and recycled concrete are available. In it around 500,000 tons of recycled coarse aggregates are available (Cement Concrete & Aggregates Australia, 2008).

There are many uses of recycled aggregates. In some instances they are used for basic applications as a fill material and in some instances are used in structural concrete. Some of the industrial applications of recycled aggregates that are obtained from demolished concrete are,

- General bulk fill (Yong & Teo, 2009)
- Landscaping (Silva et al, 2014)
- Bank protection (Yong & Teo, 2009)
- Road construction (Yong & Teo, 2009)
- Noise barriers (Yong & Teo, 2009)
- Embankments (Yong & Teo, 2009)
- backfill for retaining walls (Limbachiya et al, 2004)
- Producing sands (Premasiri et al, 2013)

- bituminous surface pavements (Silva et al, 2014)
- hydraulically bound layers (Silva et al, 2014)
- Pipe beddings – suitably graded recycled aggregate is used in pipe bedding.
- Capping applications (Premasiri et al, 2013)
- Crushed recycled concrete are used as the dry aggregate for brand new concrete if it is free of contaminants (Premasiri et al, 2013)
- Crushed concrete are used for laying of pathways, filling up of ruts on roads or rammed into soft earth to harden the ground (Premasiri et al, 2013)
- Cementitious mortars (Silva et al, 2014)

The Hong Kong Wetland Park shown in Figure 2.3, is a conservation, tourism and educational facility that is situated at the north-western section of Hong Kong. It is close to the border between Shenzhen of the mainland and Hong Kong. The park has a 10,000 square meter visitor center that includes AV theatres, cafes, souvenir shops, exhibition gallery; children play areas, resource centers and class rooms. In the construction of the Hong Kong Wetland Park natural coarse aggregates were replaced to some extent with recycled coarse aggregates in the structural concrete used. The highest grade of concrete used in this project was grade 35 concrete. The levels of replacement of RCA with NCA according to the specifications were as such, for concrete grades 20 or below 100% recycled coarse aggregates were used and for concrete grades between grade 25 and grade 35, 20% of natural coarse aggregates were replaced with recycled coarse aggregates. According to Fong, Yeung and Poon (2004), to compensate the high initial free water content needed by the RCA and also to maintain a constant water-cement ratio the cement content added in to the concrete mix was increased by roughly 4% during the construction of the Hong Kong Wetland Park.

Figure 2. 3: Hong Kong Wetland Park

Source: (Hong Kong Tourism Board, 2015)

The Samwoh Corporation in Singapore is one of the best companies when it comes to maintenance and construction of aircraft, road and seaport pavement. It is a company that strives to obtain sustainability in any endeavor it takes up. It has invested heavily on many research work and tests to promote green building technology. Hence complying with the rules and regulations set by the government on sustainable development.

The Samwoh Group has two interlinked construction waste recovery facilities placed in Sarimbun Recycling Park, Figure 2.4 and Figure 2.5. The main objective of these recycling plants is to process the construction and demolition waste and obtain recycled aggregates. The recycled aggregates are used in road construction and as an alternative material for virgin aggregates in concrete production.

Figure 2. 4: Construction Waste Recovery Facilities Placed in Sarimbun Recycling Park

Source: (Samwoh, 2015)

Figure 2. 5: Construction Waste Recovery Facilities Placed in Sarimbun Recycling Park

Source: (Samwoh, 2015)

The Eco-Green Building is a three story building that is used as the office and research laboratory of the Samwoh Corporation, Figure 2.6. The specialty of this building is that it’s made with 100% recycled concrete aggregate (Samwoh, 2010). No concrete structure has ever been made with such a high percentage of recycled concrete aggregates which makes this structure a shining beam of ray for the use of recycled concrete aggregate in structural concrete. This magnificent masterpiece has taken the green construction technology in to a whole new level.

Figure 2. 6: Samwoh Eco-Green Building

Source: (Samwoh, 2010)

The Eco-Green Building is situated at the Samwoh Eco-Green Park. The Samwoh Eco-Green Park also consists of a ready mix concrete plant that can make eco-concrete and an asphalt recycling plant (Samwoh, 2010).

The Tokyo Electric Power Company (TEPCO) in Japan obtained the approval from the Ministry of Land Infrastructure and Transport (MLIT) to mix natural coarse aggregates with recycled coarse aggregates and produce structural concrete in order to be used in two projects (Dosho, 2007). In the first project recycled coarse aggregate concrete was used in the Symbiosis Building Biotope Soga which was placed in the Chiba Heating Power area, Figure 2.7. The concrete used in this project had a design strength of 24 N/mm^2 where, 30% of natural coarse aggregates were replaced with recycled coarse aggregates. Around 200 cubic meters of concrete was used in this project. In the second project recycled coarse aggregate concrete was used in the Incinerator Building which was placed in the Yokohama Thermal Power Plant premises, Figure 2.8. The concrete used in this project had a design strength of

21-33 N/mm^2 where, 50% of natural coarse aggregates were replaced with recycled coarse aggregates. Around 1000 cubic meters of concrete was used in this project.

Figure 2. 7: Project No.1; Symbiosis Building Biotope Soga Installed in the Chiba Heating Power Area

Source: (Dosho, 2007)

Figure 2. 8: Project No.2; Incinerator Building Installed in the Yokohama Thermal Power Plant Premises

Source: (Dosho, 2007)

The Waldspirale residential building in Darmstadt, Germany was built in the 1990's, Figure 2.9. The recycled aggregate concrete was used in all in-door structural elements and in some instances for foundation slabs. The quality of concrete used was mainly either from grade 25-grade 30 or grade 30-grade 37. Around 12000 cubic meters of recycled aggregate concrete was used in the Waldspirale residential building (Marinkovi, Ignjatovi, Radonjanin & Malešev, 2010).

Figure 2. 9: Waldspirale Residential Building in Darmstadt, Germany

Source: (Marinkovi et al, 2010)

The Vilbeler Weg office building built in Darmstadt, Germany is another building where recycled aggregate concrete has been used in its construction, figur 2.10. It contains an open multi-storey garage. Reinforced concrete structures were constructed with recycled aggregate concrete. Around 480 cubic meters of recycled aggregate concrete was used (Marinkovi et al, 2010).

Figure 2. 10: Vilbeler Weg Office Building Built in Darmstadt, Germany

Source: (Marinkovi et al, 2010)

The BRE office building in Watford was the first building to be made in the United Kingdom that used recycled aggregate concrete, Figure 2.11. Around 15000 cubic meters of recycled aggregate concrete was used to make the floor slabs, waffle floors, foundations and structural columns. A grade 25 concrete mix designed to give a slump of 75 mm was used in the foundation work. A grade 35 concrete mix designed to give a slump of 75 mm was used for the floor slabs (Marinkovi et al, 2010).

Figure 2. 11: The BRE Office Building in Watford, UK

Source: (Marinkovi et al, 2010)

2.2.5. Methods Used to Process Construction and Demolition Waste to Obtain Recycle Aggregates

A concrete structure can be demolished by mainly two methods (Silva et al, 2014). The first method is the conventional method where the structure is demolished as it is without the removal of any materials such as glass, wood, roof tile, floor tiles, plastic pipes, wires and many more that can be reused or recycled. The second method is the selective demolition method where materials such as glass, wood, roof tile, floor tiles, plastic pipes, wires and many more that can be reused or recycled is removed prior to the demolition of the building. This method is more sustainable and environmentally friendly since less waste is sent to landfill areas. The selective demolition method is viewed as less economical and practical in the construction industry. The profitability of selective demolition mainly depends upon the tipping fees, labor costs and market prices for recovered material in an area. The selective demolition approach is stated to be more economical in the long run.

It should be highlighted that partial selective demolition where the non-structural materials are recovered for recycling and the rest is demolished by using the conventional method and disposed in landfills will have a negative impact on the environment. This is mainly due to the fact that vehicles are used to transport the crushed waste for long distances thereby polluting the environment. Silva, de Brito and Dhir (2014), states that for there to be a positive impact on the environment at least 90% of the concrete structure needs to be recovered and reused in new construction work.

The selective demolition method is the best method to reduce the amount of contaminants present in the construction and demolition waste materials that are been processed in recycling plants. The recycling industry promotes this methodology because otherwise the end product will be of an inferior quality and its market value will drop, which will not be economically viable to the recycling plant. Hence a prudent quality control approach has been carried out by the recycling plant where depending on the composition, contaminants present, origin and amount of material the recycling plants charge varying fees (Silva et al, 2014).

Mainly there are two types of recycling plants. They are stationary recycling plants and mobile recycling plants. The crushing process of construction and demolition waste to obtain recycled aggregates is similar to that used in rock quarries to produce natural concrete aggregates. The only difference is that there are magnetic separators, trash screen, log washers, water pumps, sludge tanks and many more that are used to remove the contaminants present in the construction and demolition waste ((Parekh & Modhera, 2011), (Marinkovi et al, 2010)).

The mobile recycling plant as shown in Figure 2.12, is generally used in the demolition site itself where the waste material crushed and processed by it, is reused at the same site. This method of crushing is more economical and environmentally friendly since there is no transportation cost of construction and demolition waste. The mobile crusher plant contains only one stage of crushing and is not capable of efficiently removing the contaminants present in the construction and demolition waste ((Parekh & Modhera, 2011), (Marinkovi et al, 2010)).

Figure 2. 12: Mobile Recycling Plant

Source: (Marinkovi et al, 2010)

In the stationary recycling plant the following processes are conducted to obtain recycled aggregates from construction and demolition waste (Fong et al, 2004). The construction and demolition (C&D) waste is first sent through a vibrating feeder, grizzly and trash screen where mechanical or hand sorting is carried out to remove the foreign materials such as wood, hardboard, metal, paper, plastic and etc. and to select the hard portion from the C&D waste that is suitable to be sent to the next stage of the process. The selected C&D material is then sent through a scalping screen, log washers, water pumps and sludge tanks to remove any clay or soil stuck on to them (Parekh & Modhera, 2011). Afterwards the selected C&D material will then be conveyed by a conveyor belt to a primary crusher (jaw crusher) in order to reduce the selected materials size to 200 mm or lesser than that. The crushed material is then sent through a magnetic separator, manual picking gallery and an air separator in order to remove any contaminants present before it is fed in to the secondary crusher. The cleaned material is then fed in to the secondary crusher (cone crusher) to reduce its size in to sizes lesser than 40 mm. the crushed recycled aggregates is then sent through a vibratory screen in order to separate them in to different sizes. At the end of the process the crushed recycled aggregates are stored in storage compartments or silos.

In some instances after the C&D material are sent through the primary crusher, they are sent through an impact crusher as well. This gives the crushed recycled aggregate a more rounded shape (Parekh & Modhera, 2011). In some recycling plants filter cakes are used for drainage of muddy water obtained after the washing process of the C&D waste material. Here clay, silt and soil particles contained in the washed water are removed and any clogging of drains will be avoided (Parekh & Modhera, 2011).

Japan has introduced an advanced recycling process known as the “heating and rubbing method” to further improve the quality of recycled aggregates (Parekh & Modhera, 2011). A flow chart of this process is shown in Figure 2.13. Firstly the recycled aggregates are heated to a temperature of 300^{o}C in order to remove the weak adhered mortar and cement particles on the surface of the recycled aggregates. The recycled aggregates are then sent through two cylinders that are eccentrically spinning at high speed. Here the attached mortar will be removed from the recycled aggregates due to the grinding effect. Afterwards the recycled aggregates would undergo straight forward mechanical grinding. Here the recycled aggregates are sent in to a drum that contains iron balls.

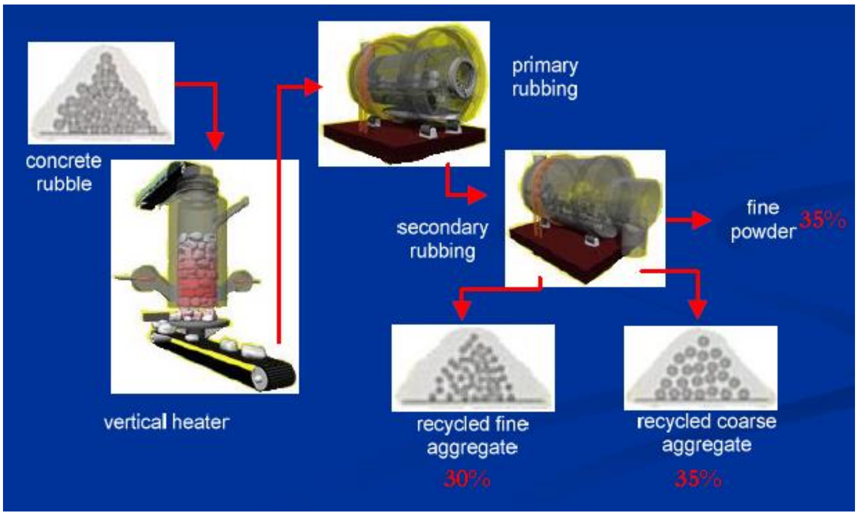


Figure 2. 13: Heating and Rubbing Method

Source: (Parekh & Modhera, 2011)

2.2.6. Properties of Recycled Coarse Aggregates (RCA)

2.2.6.1. Chemical Properties

2.2.6.1.1. Sulphate Content

The main source of sulphate present in RCA is from gypsum and crushed clay bricks. The main cause of gypsum found in RCA is due to the plasterwork used. Gypsum has a low hardness, low density and is soluble in water. Therefore there are many draw backs that the concrete would face due to the presence of gypsum. Silva et al, (2014), suggests that due to the attached mortar RCA has a higher sulphate concentration than NCA. It was further stated that the adhered mortar content has a strong correlation with the sulphate content present in RCA. The sulphate contained in RCA is water soluble. The sulphate found in the RCA have a high reactivity, hence this could lead to expensive reactions in the concrete made with the use of RCA that would lead to undesirable cracks in the concrete structure. According to the specifications the maximum sulphate content present in RCA by mass is limited to 0.8-1.0 % (Silva et al, 2014).

2.2.6.1.2. Chloride Content

According to Silva et al, (2014), if the source of the construction and demolition waste is from an estuarine or marine environment the RCA obtained from the processing of the C&D waste may contain a high concentration of soluble chloride in it. RCA that contains high amounts of soluble chloride is not recommended to be used in any steel reinforced concrete applications (Silva et al, 2014). Since the use of such contaminated RCA in structural concrete will trigger the corrosion of steel reinforcement bars and increase the deterioration of the concrete. Hence it is of acute importance to restrict the amount of chloride ions that is present in RCA therefore prudent care needs to be taken when processing such C&D waste. The chloride ions present in the RCA can be easily leached in to water, hence if the contaminated RCA is soaked in water and is thoroughly washed the concentration of chloride ions present can be reduced (Silva et al, 2014). It is mainly due to the fact that chloride ions are not linked with the hard cementitous micro structure hence its removal by washing the RCA can be easily achieved. When using RCA where chloride ions are linked with the calcium silicate or calcium aluminate phases of the old adhered mortar on the surface of RCA, precautions need to be taken to limit the chloride content between 0.01-1.0 % by mass of cement (Silva et al, 2014).

2.2.6.1.3. Alkali Content

The presence of reactive silica in aggregates and the presence of alkalis in cement may react together and cause detrimental effects to the concrete (Silva et al, 2014). Hence prudent care needs to be taken to confine the amount of alkali present in the materials used to make concrete. When considering RCA it can contain alkali rich hydrated cement. According to Silva et al, (2014), unless it is distinctly mentioned that RCA is not reactive, RCA should be categorized as a potentially reactive aggregate.

2.2.6.1.4. Leachability

Processed construction and demolition waste that have not gone through a selective demolition process and depending on the source of the waste may contain contaminants such as treated wood, asbestos, lead-based paint, mercury present in fluorescent lamps, admixtures and various other hazardous materials and elements that are detrimental to all living beings (Silva et al, 2014). If such recycled materials obtained from uncontrolled processing is used in road construction or any type of ground based work these hazardous materials can easily get leached in to the ground water causing a catastrophic disaster to all living beings in the near vicinity. According to Silva et al, (2014), if the recycled materials are to be used in applications that can lead to any kind of Leachability, the method used to demolish old structures and the method used to process the C&D waste is of utmost importance.

2.2.6.2. Physical Properties

2.2.6.2.1. Strength of Parent Concrete

The knowledge on the properties of the parent concrete of RCA is mostly unknown. The water-cement ratio, origin of the aggregates used and their gradation, types of admixtures used and the proportions used, the designed strength and many more are some of the important data that is unknown of the parent concrete (Parekh & Modhera, 2011).

Work conducted by Sami et al, has stated that high quality parent concrete will produce high quality second generation concrete (Tabsh & Abdelfatah, 2009). In order for the concrete made with RCA to gain an adequate strength the grade of the parent concrete of RCA used should at least be of grade 25. It should also be brought to note that according to Yadav & Pathak, (2009), RCA obtained from a high strength parent concrete will have high amounts of adhered mortar which will be detrimental to the fresh and hardened properties of the concrete (Yadav & Pathak, 2009). Hence it is of utmost importance to gather the historical data of the RCA prior to its use in concrete.

2.2.6.2.2. Adhered Mortar

The adhered mortar on the surface of the RCA is a major drawback when it comes to it been used as an alternative material for NCA in the production of structural concrete.

The adhered mortar is very porous hence the RCA has a very high water absorption capacity when compared with NCA. Hence the concrete made with RCA tends to have very low workability sometimes even zero workability can be observed (Yadav & Pathak, 2009). This is mainly due to the fact that part of the water added in to the concrete mix is been absorbed by the RCA, thereby causing a reduction of water in the cement paste hence reducing the workability and the stremgth of the concrete.

Yadav & Pathak, (2009), states that the amount of adhered mortar on the surface of RCA varies form 30% to 60%. According to de Juan and Gutiérrez (2009), the adhered mortar content depends on the size fraction of the aggregates. The amount of adhered mortar is said to be inversely proportional to the size of the aggregate. That is when the size fraction of the aggregate is small, high amounts of attached mortar is present on the surface of the RCA. The amount of adhered mortar present on the surface of RCA when its size fraction is between 4-8 mm and 8-16 mm are 33-55% and 23-44% respectively ((Yadav & Pathak, 2009), (de Juan & Gutiérrez, 2009)).

The Los Angeles Abrasion value (LAAV) and the aggregate impact value (AIV) of RCA are very much higher than that of NCA. It is mainly due to the fact that the attached mortar gets removed during the testing process of each test carried out to detect the resistance to abrasion and impact, and gets added up in to the fines. Due to the attached mortar RCA show less resistance to abrasion and impact than NCA (Premasiri et al, 2013).

It is said that by increasing the number of crushing processes in the recycling plant the amount of attached mortar on the surface of RCA can be reduced and good quality RCA can be obtained. It should be noted that this will increase the production cost of the RCA. Hence a standard needs to be brought about that will indicate the number of crushing processes needed to give the required quality of the RCA that is needed for a specific application.

Yagishita, Sano and Yamada, (1994), states that the attached mortar on the surface of the RCA can be removed by immersing the RCA in a hydrochloric solution. Here the cement paste will get dissolved in the hydrochloric acid (Yagishita, Sano & Yamada, 1994).

A thermal treatment method was designed by the Universidad Politécnica of Barcelona to remove the attached mortar on the surface of the RCA (Barra, 1996). Here the RCA is soaked in water for time duration of two hours in such away so that the adhered mortar gets saturated and not the natural aggregate. Afterwards the soaked RCA is dried in a muffle furnace for time duration of two hours at a temperature of 500^{o}C in order to evaporate the water that was absorbed by the porous mortar. This process will produce a lot of stress in the mortar hence its removal becomes easy. The dried RCA obtained from the muffle furnace is then straightaway immersed in waster.

2.2.6.2.3. Size and Shape

The types of devices used to crush the C&D waste and the number of processing stages used are the deciding factors for the shape, size and texture of the RCA (Silva et al, 2014). Usually any recycling plant mainly consists of a primary and secondary crushing stage. The primary crushing of C&D waste is mainly carried out by a jaw crusher, where it gives a good particle size distribution for the RCA. The secondary crushing is usually carried out by a cone crusher, where it gives a well-rounded and spherical shape for the RCA. If RCA are sent only through a primary crusher they will have a very sharp and flat shape. In some instances impact crushers are also used in the secondary crushing stage, where it will give the RCA a good particle size distribution and a low flakiness index (Silva et al, 2014).

RCA are usually elongated, angular and has a rough texture but NCA on the other hand are very smooth and spherical (Vyas & Bhatt, 2013). The workability of concrete made with RCA will be directly affected by the surface texture and shape of the aggregate. When angular, elongated and rough particles are used in concrete more water is needed to obtain the designed workability (Vyas & Bhatt, 2013). Since RCA have angular and elongated shapes the void content in the concrete will also increase.

2.2.6.2.4. Density

Aggregates can be characterized according to their specific gravity in to three main categories. They are normal-weight aggregates, light-weight aggregates and heavy-weight aggregates (Silva et al, 2014). For concrete production mainly Normal-weight aggregates are used. Manufactured aggregates such as recycled glass aggregates and air-cooled blast furnace slag and RCA also belong to the category of normal-weight aggregates.

The amount of adhered mortar on the surface of the RCA is inversely proportional to its density (Silva et al, 2014). The amount of mortar attached on to the surface of the RCA directly depends upon the number of crushing stages in the recycling plant. It is stated that with the increase of the crushing stages in the recycling plant the density of the recycled coarse aggregates increases. It is mainly due to the breaking up of the adhered mortar from the surface of the RCA. But with the increase in the processing stages the recycled fine aggregates density will reduce since the light weight adhered mortar will get added in to them. It should be noted that to obtain good quality recycled aggregates the processing stages should not be too little or too excessive since if not the processed aggregates might be very coarse or very fine in shape and size.

According to Silva et al, (2014), the strength of the parent concrete has an effect on the density of the resulting RCA (Silva et al, 2014).

2.2.6.2.5. Water Absorption

Water absorption of RCA is much greater than that of NCA. It is mainly due to the porous adhered mortar on the surface of the RCA. The water absorption of NCA is normally lesser than 1% hence it’s not considered important when making the calculations for the concrete mix design (Silva et al, 2014). But when RCA is used for concrete production the water absorption of it needs to be taken in to account.

The adhered mortar on the surface of the RCA is proportional to the water absorption of the RCA. The water absorption of the RCA depends on the number of processing stages in the recycling plant. Hence when C&D waste undergo a secondary crushing process the resulting RCA will show lower water absorption values than that obtained from only a primary crushing process (Silva et al, 2014).

It is also stated that if the original material was of high strength then the water absorption of the resulting RCA will have a tendency to reduce. Coarser particles of recycled aggregates have lower water absorption capacity than that of the finer particles. Since coarser particles have lesser old cement mortar than finer particles (Silva et al, 2014).

2.2.6.3. Properties of the Concrete Made With Recycled Coarse Aggregates (RCA)

2.2.6.3.1. Modulus of Elasticity

The modulus of elasticity of concrete is proportional to the compressive strength of the concrete. According to the ACI code the peak stress is supposed to occur at a strain of 0.002 (Rahal, 2005). Concrete made with the use of recycled coarse aggregate show weaker properties than that made with natural coarse aggregates. Rahal (2005), states that the strain at peak stress of recycled aggregate concrete could be greater than the value specified by the ACI code. Hence the strain at peak stress and the modulus of elasticity of recycled aggregate concrete are very crucial points that need to be analyzed in order for RCA to be used in structural concrete (Rahal, 2005).

2.2.6.3.2. Shear Strength

The shear strength mainly depends upon the ability of the coarse aggregate present in the concrete to withstand the shearing stress. The shear crack generates from the hardened cement paste and around the coarse aggregates in normal strength concrete.

But when considering high strength concrete the shear crack propagates and passes through the relatively strong cement matrix and the coarse aggregates, therefore the crack surface is relatively smooth. Since RCA are generally weaker than NCA the concrete made with it has low shear strength (Rahal, 2005).

2.2.6.3.3. Compressive Strength

Generally the compressive strength of concrete made with RCA is lesser than that made with NCA. Yadav & Pathak, (2009), states that with the increase of RCA used to make concrete the compressive strength of it reduces (Yadav & Pathak, 2009).

Many researchers conducted have concluded that RCA is a suitable alternative material to NCA. According to Limbachiya, Koulouris, Roberts and Fried, (2004), NCA can be replaced up to 30% with RCA for the production of concrete without any changes to the mix design. It was further stated that the performance of the concrete made with partial replacement of NCA with RCA was similar to that made with 100% NCA (Limbachiya et al, 2004). But it should be taken in to note that beyond 30% replacement of NCA with RCA will cause the compressive strength of the concrete to reduce.

When considering the workability and the uniformity of a concrete mix the moisture state of the aggregate plays a very important role (Poon, Shui & Lam, 2004). Since it can change the fresh concrete properties and have a detrimental effect on the hardened concrete properties. Recycled coarse aggregates (RCA) have a very high water absorption capacity hence the moisture state and the humidity level of the RCA is of substantial importance when deciding the water requirement for the concrete mix. The moisture state of the RCA is also important to determine the mixing time, compacting time and other technical parameters as such that is of utmost importance for the concrete production ((Poon et al, 2004), (Marinkovi et al, 2010)).

According to Fong et al, (2004), the concrete made with 100% RCA had a very poor workability with a slump loss of 0 mm hence it was recommended by Fong et al, (2004), to use RCA at its surface saturated dry (SSD) condition (Fong et al, 2004).

Whereas other studies conducted on the moisture state of the RCA states that it should be used at a semi saturated condition ((Barra & Vazquez, 1996) & (Yong, 2009)).

According to Pelufo, Domingo, Ulloa and Vergaraa (2009) the compressive strength of concrete made with RCA in its natural state had obtained the highest strength with comparison to the concrete made with RCA in a pre-saturated state. It was mainly due to the excess water that was present in the pre-saturated RCA that had caused a bleeding effect in the fresh concrete and hence the observed strength drop (Pelufo, Domingo, Ulloa & Vergaraa, 2009). It should be noted that the pre-saturated RCA used in this research was not in its surface saturated dry (SSD) condition (Pelufo et al, 2009). According to Barra and Vazquez (1996), the semi saturated state of the RCA can produce good quality concrete with good fresh and hardened concrete properties. It is mainly due to the fact that a much dense and solid interfacial transition zone is formed when RCA is used in its semi saturated condition (Barra & Vazquez, 1996).

The interfacial transition zone (ITZ) is a porous narrow band that is formed between the aggregate and cement paste interface. The interfacial transition zone is a deciding factor for the strength properties of any concrete made with NCA (Silva et al, 2014). When considering concrete made with RCA three types of interfacial transition zones can be identified as shown in Figure 2.14 (Younis & Pilakoutas, 2013). That is the ITZ between the old attached mortar and the natural aggregate of RCA (ITZ 1), the ITZ between the natural aggregate of RCA and the new cement paste (ITZ 2) and the ITZ between the old attached mortar on the surface of RCA and the new cement paste (ITZ 3). Due to the crushing process several micro cracks can be caused on the surface of the RCA and the ITZ between the old attached mortar and the natural aggregate of RCA, hence RCA is prone to more fragmentation than NCA (Silva et al, 2014). The interfacial transition zone has a very porous micro structure (Yadav & Pathak, 2009). It is mainly due to the fact that RCA is very porous and has a high water absorption capacity. Since the interfacial transition zone formed in RCA concrete is very porous the concrete strength property is very low. It was further stated by Yadav and Pathak (2009), that the weakest zone in RCA concrete is its interfacial transition zone.

According to Poon, Shui and Lam (2004), if the bond at the interfacial transition zone between the new cement matrix and the RCA can be made stronger the concrete made with the RCA can achieve a greater strength. Hence the negative impact caused due to the use of inferior quality aggregates for the production of concrete can be compensated (Poon et al, 2004).

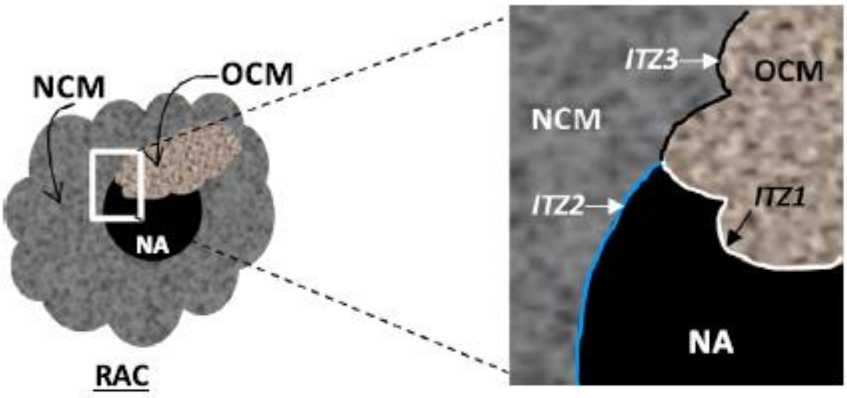


Figure 2. 14: Interfacial Transition Zones identified in RCA

Source: (Younis & Pilakoutas, 2013)

According to Chen, Yen and Chen (2003), the compressive strength of concrete made with RCA decreases with comparison to NCA at low- water cement ratios. It is mainly due to the fact that when low water-cement ratios are used the thickness of the cement paste increases hence its strength factor increases, according to the composite material theory the RCA becomes an even more weaker material therefore its bearing capacity reduces thereby resulting in a decrease in the hardened concrete properties (Chen, Yen & Chen, 2003). Chen et al, (2003), states that the compressive strength of concrete made with RCA is inversely proportional to the water-cement ratio.

On the other hand it was stated by Rahal (2005), that the strength of the concrete produced with RCA can be increased by reducing the water-cement ratio, but “water reducers" need to be added in to the mix to achieve the designed workability. A slightly larger amount of cement around 5% more than the proportion calculated in the mix design is said to be needed to give the concrete made with RCA a similar strength and workability as that made with NCA (Rahal, 2005).

The strength properties of RCA concrete made with high water-cement ratios did not depend upon the quality of the RCA but when the water-cement ratio were of low values the quality of the RCA used has a direct effect on the concrete strength properties (Parekh & Modhera, 2011). The reduction in the compressive strength is less when low grade concrete is made with RCA (Parekh & Modhera, 2011).

2.3. Rice Husk Ash (RHA)

2.3.1. Introduction

Rice is a very important food crop and an important source of calories for many around the world. It is said to be the second highest consumed maize crop in the world. There are numerous sub species of rice that exhibits characteristics which are unique to each type of rice. Paddy cultivation is carried out in over hundred countries in the world. The absolute harvested area in the world will reach up to around 158 million hectares and the annual production of paddy will reach up to 700 million tons, where by the total production of milled rice will sum up to approximately 470 million tons (Ricepedia, 2009).

The three leading food crops in the world are mainly wheat, rice and maize. 42% from the total calories been consumed by the existing human population in the world is made up with these three food crops. Rice is the most vital source of calories for those in developing countries. Half of the world's population considers rice as their staple food. In it approximately 3.5 million people consume it in order to satisfy more than 20% of their daily calorie needs (Ricepedia, 2009). Africa and Latin America are said to be the fastest growing continents where rice is becoming a staple meal. Due to the economic growth, levels of economy and the increase in the population the consumption of rice in the world is still said to remain firm and strong (Ricepedia, 2009).

Asia cultivates and consumes approximately 90% of the world’s paddy cultivation that is around 640 million tons of rice been produced every year (Ricepedia, 2009). China, India and South-east Asia are the largest rice producing regions in the world. China is said to produce more rice than India, even though the area used to harvest in China is lesser than that of India. It is mainly due to the fact that almost all the areas used to grow rice in China have a good irrigation system than in India (Ricepedia, 2009). Rice production in South America and Sub-Saharan African regions are 25 million tons and 19 million tons respectively. The staple meal of roughly 2.4 billion people in this region alone is rice (Food and Agriculture Organization of the United Nations, 1998). Even though Asia grows the highest amount of rice, it is usually grown in small farms having a land area of 0.5-3 ha (Ricepedia, 2009).

In poor rain-fed conditions the rice yield is lesser than 1ton/ha but in intense temperature conditions and good irrigation systems the rice yield can be greater than 10 ton/ha (Ricepedia, 2009). In developing countries many families whose livelihood is rice farming have a very low income due to the small and in some instances dwindling size of the farm area been used to grow rice. In low altitude desert like areas that has a good source of solar energy or high latitude areas where the day is long and acute farming technologies are been used, the production of rice is very high. Places such as the Nile delta, northern California, Spain, Italy, southwestern Australia and Hokkaido in Japan (Ricepedia, 2009).

The rice plant has similar characteristics as wheat and oats but it can be grown in very wet soil or in flooded soil. The flowers developed in the rice plant are called panicles which can be pollinated by wind. The pollinated flowers will then be converted in to rice grains. Rice plants are said to be perennial but in order to get a better yield farmers plant new rice seeds every season (Ricepedia, 2009).

A rice seed contains a rice husk which is inedible and is the outer covering of the rice grain and the rice grain which is edible. In order obtain the rice grain the rice husk needs to be removed. A layer of bran is found underneath the rice husk protecting the rice grain. When the bran layer is still attached to the rice grain it is known as ‘brown rice’ and when the bran layer is removed it is known as ‘white rice'. The weight of a single rice seed is said to be approximately 10-45 mg in which the rice husk would roughly sum-up to 20% of the total weight (Ricepedia, 2009).

Parts of the rice seed is shown in Figure 2.15.

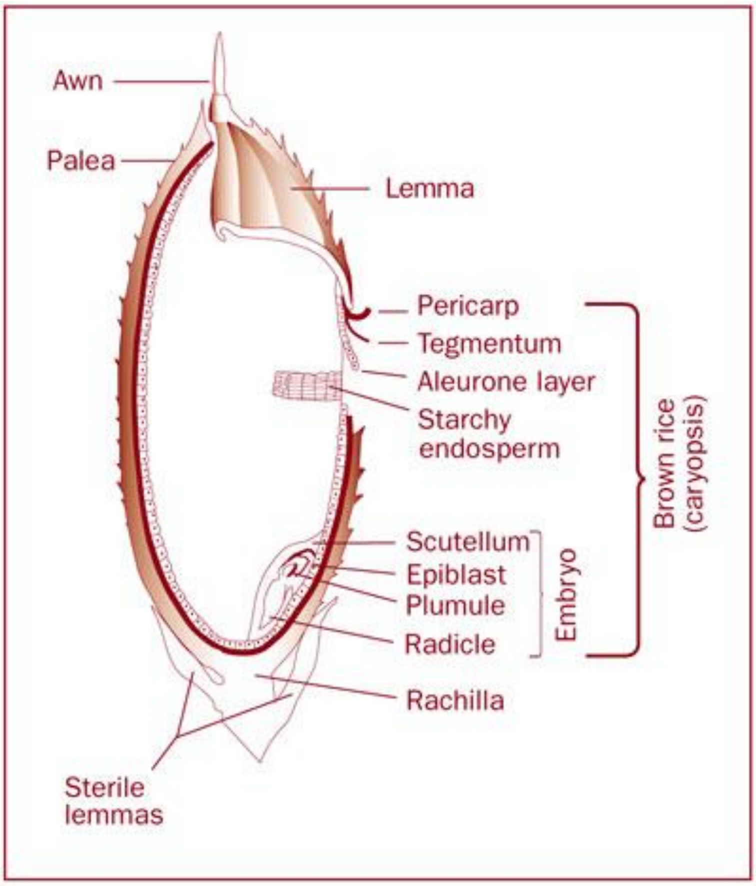


Figure 2. 15: Parts of the Rice Seed

Source: (Ricepedia, 2009)

In the production of rice, the milling process is a very important stage which would derive the quality of the rice and the color of the rice (Ricepedia, 2009). It is a very vital step because it removes the inedible rice husk from the rice grain. During the milling process if the husk was only removed the resultant product is known as 'brown rice' and if it was further polished where the bran layer was also removed the resultant product is known as 'white rice'. The rice milling process is mainly categorized in to village rice mills and commercial rice mills depending on the final consumption of the rice (Ricepedia, 2009). Village rice mills will consist of a process that contains one or two stages whereas the commercial rice mill will consist of a process that contains multiple stages.

The parboiling of rice is carried out in many counties such as South Africa, Guinea, Nigeria, Spain, Italy, France, Switzerland, India, Pakistan, Bangladesh, Nepal, Sri Lanka, Malaysia and Myanmar (Pillaiyar, 1981). Approximately 50% of the world's paddy cultivation undergoes the parboiling process (Pillaiyar, 1981). In the parboiling process the rice grain is partially boiled in its rice hull itself. Soaking, steaming and drying are the main three stages in the parboiling process. Parboiled rice is more nutritious and has a better texture and quality. Thiamin present in the bran layer is absorbed in to the endosperm of the rice grain (Kyritsi, Tzia & Karathanos, 2011). Therefore it is said that around 80% of nutritional value present in red rice is present in parboiled white rice as well. After the parboiling process the bran layer around the surface of the rice grain becomes oily therefore the parboiled rice is not polished by a mechanical process due to the technical difficulties faced with the bran layer. But the polishing of parboiled rice can be easily carried out by hand.

There are three major types of processes used in the industry to parboil rice (RICELAND INTERNATIONAL LIMITED, 2011). They are,

- The conventional method

  The main stages in this process are soaking, draining, steaming at atmospheric pressure, drying and milling.

- The dry-heat method

  The dry-heat method has the similar stags as the conventional method but instead of the steaming stage seen in the previous method it has a heating stage. In the heating stage dry hot air or dry heated sand is used to cook the rice prior to the drying stage.

- The pressure-steaming parboiling method

This method is widely used in the industry. In this method after the soaking stage the rice is steamed by pressurized steam prior to the latter stages of drying and milling.

A graphical presentation of nutrition transfer from the bran layer in to the rice grain during the parboiling process is shown in Figure 2.16.

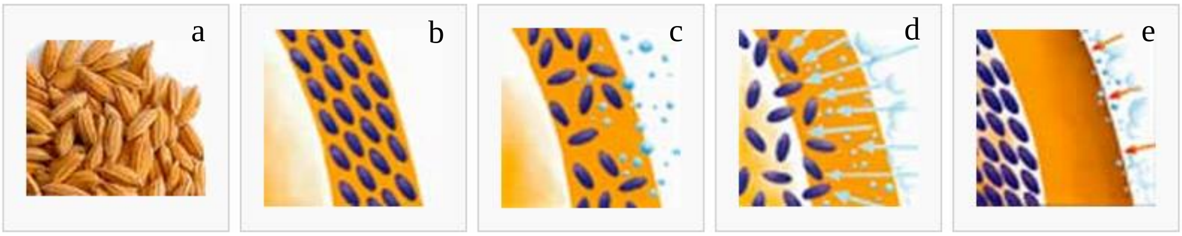


Figure 2. 16: Graphical Presentation of Nutrition Transfer from the Bran Layer in to the Rice Grain during the Parboiling Process

Source: (Parboiled rice, n.d.)

a: Raw paddy rice

b: Vitamins and minerals present in the bran

c: When raw paddy rice is put in a vacuum, rice loses all the air present in it. Afterwards when inside a warm water bath the nutrients present in the bran layer becomes more soluble and moves away from the bran layer

d: In order for these nutrients to shift into the kernel, air pressure and hot steam are used, or else the nutrients will get washed out into the water

e: Around 80% of nutritional value present in red rice is present in parboiled white rice

After the milling process of paddy 78% by weight is obtained as bran, rice and broken rice the remnant 22% is obtained as rice husk which is a waste product of the milling process. Rice husk is generally used as a fuel in order to produce steam required for the parboiling process. During the firing process of rice husk 75% by weight is removed as organic volatile matter and the remaining 25% is obtained as rice husk ash (RHA) ((Nagrale et al, 2012), (Kumar et al, 2012)). According to

Ngarale et al., the RHA generated during the parboiling process is said to contain approximately 85-90 % of amorphous silica.

The chemical composition of rice husk is very much alike that of other organic fibers. It mainly consists of, lignin ($C_7H_{10}O_3$) which is a polymer of phenol, cellulose ($C_5H_{10}0_5$) which is a polymer of glucose, hemicellulose ($C_5H_8O_4$) which is a polymer of xylose and silica (Hwang & Wu, 1989). Depending on the specie of the rice the amount of hemicellulose and lignin present will vary.

2.3.2. Production of RHA

It is stated by Rukzon et al., that if the firing of rice husk is carried out under controlled temperature and time, the RHA produced will be highly reactive and if properly ground to an adequate fineness will exhibit very good pozzolanic properties (Rukzon & Chindaprasirt, 2008). It should be highlighted that rice husk do not have any pozzolanic properties. In order to produce good quality RHA the firing temperature and the firing time duration are very vital parameters (Robert, 1990). When rice husk is fired in a controlled burning system where the optimum firing temperature and time duration is used the RHA will contain approximately 80-95% silica, 1-2 % K_2O and un-burnt carbon (depending on the firing condition). When the burning temperature of rice husk is too low a significant proportion of un-burnt carbon is produced. The surface of RHA is very porous. When RHA that contains high percentages of carbon are used to produce concrete or mortar there will be a significant impact on the initial setting and final setting of the cement paste and it will have a detrimental effect on the strength gain ((ASTM International, 1989), 84). Hence according to the ASTM C618-89, the carbon present in RHA should not exceed 10% in order for it to belong to a ‘type N’ pozzolan. It is advisable that during the firing process of rice husk it is best to supply a sufficient amount of air so that the formation of carbon in RHA will be low.

According to many studies the optimum firing temperature of rice husk which produces RHA that contains the highest percentage of reactive amorphous silica is between 500-750^{o}C ((Nagrale et al, 2012), (Cook, 1983) and (Cook, 1980)). According to Ramezanianpour et al., the best combination of firing temperature and firing time duration is 650^{o}C and 60 minutes in order to obtain good quality RHA that is highly reactive.

When the firing temperature of rice husk is beyond 600-700^{o}C there is a very high aptness for a crystalline formation to occur (Spence & Cook, 1983). The crystalline formation will contain wollastonite and alpha-quartz if the firing temperature is between 700-800^{o}C and will contain wollastonite, beta (Ca_3SiO_3), tridymite and beta-quartz if the firing temperature is between 900-1000^{o}C (Spence & Cook, 1983). According to Robert et al., when the husk is fired at a temperature of 700^{o}C a very distinct color change of grayish color to a pinkish color can be observed in the RHA and is said to have particles containing spherical shapes.

In order to have a good control on the firing temperature simple furnaces that use three main orifices to maintain and control the temperature have been produced. Incinerators made of fired clay bricks can be used to burn rice husk at temperatures below 700^{o}C without any substantial amounts of carbon present in the ash. But when the temperature increases beyond 650^{o}C rapid cooling of RHA needs to be done, that is basically to remove the RHA from the incinerator and spread it on the ground in order for it to cool (Nagrale, Hajare & Modak, 2012). A pyrometer is used to observe the temperature in the incinerator. The pyrometer is an apparatus used in the industry in order to measure high temperatures. To produce 1 ton of RHA per day at least 3-4 incinerators need to be used (Nagrale et al, 2012).

A photograph and a schematic diagram of rice husk ash furnace is shown in Figure 2.17.

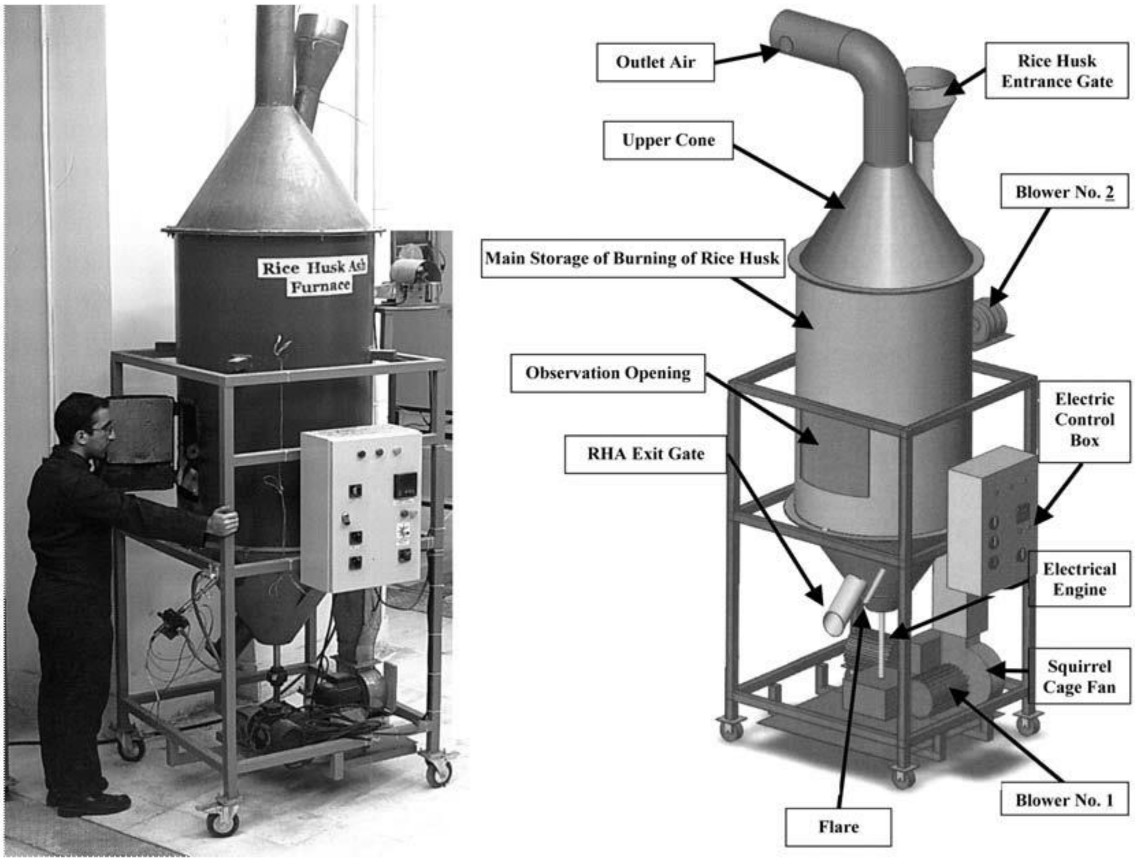


Figure 2. 17: A Photograph and a Schematic Diagram of Rice Husk Ash Furnace

Source: (Ramezanianpour, Mahdi & Ahmadibeni, 2009)

The use of simple furnaces to burn rice husk has many advantages as well as disadvantages. They are,

Advantages

- It is very simple and less costly to make
- Very easy to handle
- It can produce RHA of an adequate quality

Disadvantages

- The production of RHA per day is very small
- Constant supervision is needed
- The energy value of the rice husk is not made use of in this process

Rice husk is said to contain an energy value that is half that of coal hence it can be used as a source of energy. Currently furnaces and kilns are designed for various other works than parboiling of rice, where the energy available in the rice husk can be utilized and the firing temperature can be controlled to be below 700^{o}C (Nagrale et al, 2012).

After the firing process of rice husk the RHA obtained needs to be ground in to a fine powder in order for it to be used as a pozzolan. It is stated by Nagrale et al., that RHA needs to be ground to fineness that is as ordinary Portland cement or as much finer that that in order for it to be a reactive pozzolan. Normally a hammer mill or ball mill is used to grind RHA. According to some studies the fineness of RHA after grinding needs to be around 10000cm^2/g, but it is said to take time duration of 1.5-5 hours (Spence & Cook, 1983). According to Nagrale et al., the fineness requirements of grade 1 and grade 2 pozzolans given in the Indian standards for pozzolana are 320m^2/kg and 250m^2/kg respectively. RHA obtained in the crystalline form is harder than that obtained in the amorphous form and hence will need to be ground for longer time duration in order for it to achieve the required fineness (Nagrale et al, 2012).

2.3.3. Applications of Rice Husk and Rice Husk Ash (RHA)

2.3.3.1. Applications of Rice Husk

<u>Rice husk is used as a fuel in power plants</u>

According to Nagrale et al., rice husk is said to have better prospects in the use as an annually renewable alternative energy source since it has an energy value that is half that of coal (Nagrale et al, 2012). Rice husk is mainly used in boilers as a fuel in the parboiling process of paddy, to produce steam in order to generate power; it is also used as a fuel in brick kilns and as an alternative fuel for house hold uses (Sathish, 2012).

In most developing countries the parboiling process of paddy is carried out in low capacity boilers. Rice husk is manually fired in these boilers. Due to uncontrolled burning the efficiency of rice husk decreases, furthermore the smoke been emitted in to the environment due to partial combustion of rice husk are factors which are not that desirable. Therefore the efficiency of the boiler and the degree of combustion of rice husk are parameters that need to be given much thought when wanting to develop a more green and sustainable firing process of rice husk (Sathish, 2012).

Rice husk can be used to produce heat by either gasification or direct combustion. It is said that by firing around 1 ton of rice husk, 1MWh of energy can be produced. Furthermore it is stated that it is very economical to use rice husk as a fuel in power plants that have a capacity of 2-10MWh (Kumar et al, 2012). But it needs to be highlighted that the use of rice husk as a fuel in order to generate power is only sustainable when commercially viable techniques are been used in the industry.

Rice husk is used to form activated carbon

There is a high percentage of hydrocarbons present in rice husk in the form of lignin and cellulose. Therefore rice husk can be used as a good alternative raw material to produce activated carbon. Activated carbon is a form of carbon processed to have a complex micro porous structure in order to have a significant level of absorption due to the increase in the surface area. Mainly a physical/thermal activation process or a chemical activation process is carried out in order to produce activated carbon with rice husk. In the physical/thermal activation of rice husk carbonization is said to be followed by the char activation where as in the chemical activation of rice husk carbonization and activation are both achieved by one step with the use of a chemical agent (Kumar et al, 2012). The chemical activation process is favored more than the physical activation method due to its high product yield and its low activation temperature (Cheenmatchaya & Kungwankunakorn, 2014).

Rice husk is used as a source of Silica and Silicon compounds

Since rice husk contains approximately 20% of silica it can be used as an economical source to produce silicon compounds. Pure silicon, silicon nitride, zeolite, silicon carbide and silicon tetrachloride are some silicon compounds that can be used with the use of rice husk (Kumar et al, 2012).

Rice husk is used to make insulating fire brick

Bricks produced with rice husk are very porous. It is mainly due to the loss of organic volatile material present in the rice husk that develops pores in the bricks during their heat treatment process. The entrapped air in the pores present in the brick will cause it to have a higher thermal insulation. Higher the amount of rice husk present in the brick will cause the brick to be more porous hence it will have a greater thermal insulation (Kumar et al, 2012).

Other uses of rice husk

Rice husk is used as a raw material to produce chemicals such as ethanol, lingo sulphonic acids, acetic acid, xylitol and furfural. It is also been used as an industrial raw material as fillers in plastics, as a building material, to produce panel boards and insulating boards. It is also been used as a polishing and cleaning agent (Kumar et al, 2012).

2.3.3.2. Applications of Rice Husk Ash (RHA)

RHA is used as a source of silica

RHA contains a high amount of silica hence it is a commercially viable raw material in the production of silicates and silica. The silica present in RHA is used as a cleaning agent in the tooth paste industry, an anti-caking agent in the food industry, as a reinforcing agent in the rubber industry and is used in cosmetics. In some instances in the production of catalyst supports, dielectric materials and super thermal insulators, silica aerogels made from RHA is used (Kumar et al, 2012). Silica present in RHA in its amorphous form plays a major role as a mineral admixture for cement due to its pozzolanic properties.

RHA is used in the cement and construction industries

Blended cement is used in the industry in order to enhance the strength and durability of building materials in a more economical and sustainable method. In blended cement a part of the expensive ordinary Portland cement is replaced with a commercially viable environmentally friendly alternative material that can enhance the properties of the cement paste. Blending of reactive RHA with cement is a famous concept in the construction industry and is been recommended in many international building codes. It can be used as a substitute for silica fume and is a common admixture to produce economical concrete (Kumar et al, 2012). Many studies have been carried out in this area and have come to the conclusion that RHA can be used as a very good pozzolan, it can increase the compressive strength and flexural strength of concrete, reduce the permeability of concrete produced with RHA, increase the resistance to undesired chemical attacks, it can make a denser concrete, it can increase the workability of concrete, increase the durability of concrete, it can also reduce the heat flow through the concrete and many more ((Tomoshige, Ashitani, Yatsukawa, Nagase, Kato & Sakai, 2003), (Givi et al, 2010)).

RHA is used in the steel industry

RHA is used in the production process of high grade flat steel. RHA has very good insulating properties such as high meting point, low thermal conductivity, high porosity and low bulk density. In order to insulate the tundish container RHA is used as tundish powder. This will hinder the molten steel from rapid cooing and will cause the molten steel to uniformly solidify during the casting process (Kumar et al, 2012).

RHA is used in the ceramic and refractory industry

Due to the insulating properties of RHA it is used to produce refractory bricks and low-cost light weight insulating boards (Kumar et al, 2012). Since RHA contains a high percentage of silica it is used as a source of silica in the production of cordierite. According to Kumar et al., when the kaolinite in the mixture is replaced with RHA, at a lower crystalizing temperature a high cordierite yield can be obtained. Here the activation of energy for the crystallization process is also reduced.

Other uses of RHA

The Indian Space Research Organization has found out an effective and efficient method to extract the silica present in RHA. Silica extracted by this method is said to be of a very pure form that it can even be used to produce silicon chips. RHA demonstrates very good insulating and absorbent properties which is very useful in many industries. It is used to vulcanize rubber, to purify water, as an insect control in stored food, as a flue gas desulphurization absorbent, to absorb oil spills, as a carrier for insecticides and as a flame retardant.

2.3.4. Hydration Reaction of Cement and the Pozzolanic Reaction

According to the ASTM Specification C618-89, a pozzolan is said to be a “siliceous or siliceous and aluminous materials which in themselves contain little or no cementitious value but will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties”. If a natural pozzolan is to be used as an admixture in Portland cement or to replace Portland cement in a concrete mix it needs to adhere to the specified physical and chemical requirements given in Table 2.1, which is prescribed in the ASTM C618-89. In some instances even though the pozzolanic material do not adhere to some of the requirements given in Table 2.1, it can still perform well when used in low-cost constructions. According to Robert et al., it is stated that in order to produce building materials with adequate durability and strength, the pozzolans should at least achieve a pozzolanic activity index (PAI) lesser than 5.5 when tested with lime.

Table 2. 1: Requirements for a ‘Type N’ Pozzolan to be Used as a Mineral Admixture in Portland cement Concrete According to The ASTM C618-89

SiO2 + A1203 + Fe2O3i minimum (%)	**70.0**
SO3i maximum (%)	4.0
Moisture content, maximum (%)	3.0
Loss on ignition, maximum, (%)	10.0
Amount retained, wet-sieve on 45µm sieve, maximum, (%)	34
Pozzolanic activity index, Portland cement, at 28 days, minimum % of control	75
Pozzolanic activity index, with lime, minimum (Mpa)	5.5
Water requirement, maximum, % of control	115
Autoclave expansion or contraction, maximum, %	0.8
Specific gravity, maximum variation from average, %	5
Percent retained on 45µm sieve, maximum variation, percentage points from average	5
Optional requirements	
Increase of drying shrinkage of mortar bars at 28 days, maximum %	0.03
Reduction of mortar expansion at 14 days in alkali expansion test, minimum %	75
Mortar expansion at 14 days in alkali expansion test maximum %	0.020

Source: (ASTM International, 1989)

2.3.4.1. Hydration Reaction of Cement

Cement is formed through a milling process where clinker is mixed with Calcium Sulphate. Clinker is a mineral mixture of Silica Oxide, Alumina, Calcium Oxide and iron that underwent a synthesis process under high temperature. The main compounds of Portland cement are Tricalcium-silicate ($3CaO.SiO_2$ or C_3S), Dicalcium-silicate ($2CaO.SiO_2$ or C_2S), Tricalcium-aluminate ($3CaO.Al_2O_3$ or C_3A) and Tetracalcium-aluminoferrite ($4CaO.Al_2O_3.Fe_2O_3$ or C_4AF) (Neville, 2011).

Ordinary Portland cement is a greyish powder having a particle size range of 1-50 μm (Nastaranpoor, 2013).

When water is added to cement the combination of the compounds present in Portland cement with water is known as the hydration reaction. Products of hydration initially are plastic and with time forms in to a hard and firm mass known as the hydrated cement paste. The hydration reaction of cement is exothermic. The quantity of heat released by the hydration of every gram of cement is known as the exothermal heat. The heat produced by the hydration reaction directly depends upon the temperature the reaction had occurred and the compounds present in the cement (Ramezanianpour et al, 1989).

The major compounds present in cement that plays an important role in the strength gain of the hydrated cement paste are C_3S and C_2S. The initial strength gain of hardened cement paste is due to C_3S, since it reacts much faster than C_2S. According to Neville (2011) the C_3S compound undergoes the hydrolysis reaction and the resultant product is initially said to be a calcium silicate that is of a lower basicity and with time $C_3S_2H_3$ will produced and the lime produced will be released out as $Ca(OH)_2$. The slow intrinsic rate of reaction is said to control the hydration reaction of C_2S whereas the rate of diffusion of ions through the overlying hydrate films is said to control the hydration reaction of C_3S (Neville, 2011). The strength developments of the hardened cement paste due to the hydration reaction of C_2S occur after an age of 7days (Nastaranpoor, 2013). The final products of hydration of C_3S and C_2S are $C_3S_2H_3$ and $Ca(OH)_2$. Calcium-silicate-hydrates are known as 'Tobermorite gel' since it is said to be similar to the mineral 'Tobermorite' found in the nature (Robert, 1990). For the hydration reaction of both C_3S and C_2S compounds a similar quantity of water is roughly needed. C_3S is said to produce a higher amount of $Ca(OH)_2$ than that produced from C_2S (Neville, 2011). The hydration reaction of C_3S and C_2S can be shown as follows,

For C_3S:

$2C_3S + 6H \rightarrow C_3S_2H_3 + 3Ca(OH)_2$

The corresponding masses involved are:

$100 + 24 \rightarrow 75 + 49$

For C_2S:

$2C_2S + 4H \rightarrow C_3S_2H_3 + Ca(OH)_2$

The corresponding masses involved are:

$100 + 21 \rightarrow 99 + 22$

There is a violent reaction between the pure C_3A and water which causes the cement paste to stiffen instantly. This is known as flash setting. Gypsum ($CaSo_4.2H_2O$) is added in to the cement clinker in order to avert this form occurring. C_3A sets faster than the calcium-silicates.

The hydration reaction of C_3A is as follow (Nastaranpoor, 2013):

$C_3A + 6H \rightarrow C_3AH_6$

The corresponding masses involved are:

$100 + 24 \rightarrow 75$

In the initial stages of hardening of the cement paste the highest heat generation occurs due to C_3A. It is a compound that helps the cement paste to achieve strength in the early ages but afterwards has no impact on the strength gain of cement. High percentages of C_3A present in the cement will be detrimental to the durability of the hardened cement paste in the presence of water and soils that contain sulfates. C_3A and C_4AF react with gypsum and produce calcium-sulfoaluminate and calcium-sulfoferrite. The presence of these resultant compounds will speed up the hydration reaction of silicates. It needs to be highlighted that the amount of gypsum been added in to the cement clinker should take place with a lot of care. Excess gypsum will cause the expansion of the hardened cement paste and its deterioration. Concrete produced with cement that had a high amount of C_3A is very susceptible to get deteriorated due to the formation of Ettringite by the sulfate attack.

The sulfate attack is as follow (Ramasamy, 2011):

Sulphate + $Ca(OH)_2$ → Gypsum ($CaSO_4 \cdot 2H_2O$)

Gypsum ($CaSO_4 \cdot 2H_2O$) + C_3A → Ettringite ($Ca_6Al_2(SO_4)_3(OH)_{12} \cdot 26H_2O$) + monosulpho-aluminate

C_3A and C_4AF compounds act as a flux in the production of cement. These compounds acts as a flux to lower the temperature needed to burn the clinker and to help make the combination of lime with silica much faster and easier. But when a higher percentage of C_3A is present the grinding process of clinker will require a higher energy. C_3A can easily get combined with Cl^{-1} ions hence increasing the resistance against corrosion.

Four main phases can be observed in the hydrated cement paste. They are,

1. Calcium silicate hydrates

Calcium silicate hydrates are denoted by C-S-H. The molar ratio between C:S is not exactly known due to the variation of test results obtained when different test method are used. It is said that when the C:S ratio is analyzed by applying a chemical extraction method it will show a value of 1.5 and when the C:S ratio is analyzed by applying a thermo gravimetric method it will give a value of 2.0 (Neville, 2011). Other compounds and elements present in cement have a direct effect on the C:S ratio. The C:S ratio is also said to vary with time (Neville, 2011). C-S-H is said to make up approximately 50-60% of the total volume of completely hydrated cement paste, hence the properties of the hardened cement paste greatly depends upon it (Nastaranpoor, 2013). C-S-H may either have a weak fiber like crystal structure or a well bonded coherent structure. At the early stages C-S-H was said to relate to the “Tobermorite gel” due to the structural resemblances but not anymore ((Neville, 2011), (Nastaranpoor, 2013)).

2. Calcium hydroxide

From the total volume of the solid hydrated cement paste 20-25 % of volume is made up with $Ca(OH)_2$. It has a plate like structure. It is stated that the structure of $Ca(OH)_2$ depends upon the heat of hydration, volume accessible in the paste and the presence of any impurities in the paste. $Ca(OH)_2$ is coarser and has a lesser specific surface area than C-S-H crystals hence the effect it has on the strength gain of the hardened cement paste is very low. High amounts of $Ca(OH)_2$ present in the hardened cement paste is detrimental to its durability. It is mainly due to its high susceptibility to react with acid and sulfates (Ramezanianpour et al, 1989).

3. Calcium aluminate sulfate

From the total volume of the solid hydrated cement paste 15-20 % of volume is made up with calcium aluminate sulfate. Hence it has a lesser effect on the hardened cement paste. According to Nastaranpoor et al., calcium aluminate sulfate can be written as C_6AS_3-H_{32}. Monosulfate and ettringite are the most commonly found AFm phase and AFt phase in hydrated cement paste respectively (UNDERSTANDING CEMENT, 2005). Monosulfate is said to belong to the AFm phase because it contains one molecule of anhydrate as shown in its chemical formula $C_3A.CaSO4.12H_2O$ and ettringite is said to belong to the AFt phase because it contains three molecule of anhydrate as shown in its chemical formula $C_3A.3CaSO4.32H_2O$ (UNDERSTANDING CEMENT, 2005). Ettringite initially has a rod like crystal structure and with time will deform to a hexagonal plate shape structure. Monosulfate is formed in the hardened cement paste after a day or two of mixing. It should be highlighted that monosulfate and ettringite are compounds formed by calcium aluminate (C_3A), $CaSO_4$ (anhydrite) and water.

4. Non hydrated cement particles

Due to the rate of the hydration reaction of cement there may exist some non-hydrated cement particles in the hardened cement paste. The particle size of cement is said to vary between 1-50 μm. The finer cement particles will react first and afterwards the coarser particles will undergo the hydration reaction. The resultant compounds formed due to the hydration reaction of cement may crystalline around the un-hydrated cement particles due to the limited space between the constituent materials (Nastaranpoor, 2013).

2.3.4.2. Pozzolanic Reaction

Pozzolanic reaction can occur between lime-water system and Portland cement-water system. According to Robert et al., the formation of the microstructure that enhances the strength is said to be the same for both types of systems but the lime-water system is said to occur at a very slow rate (Robert, 1990). If calcium aluminate is present in the mix it will react first and produce calcium aluminate hydrates, this will result in the creation of the preliminary solid structure. Afterwards the formation of calcium silicate hydrates would occur which will enhance the solid structure by filling the voids in it and thereby toughening the entire cementitious matrix (Robert, 1990). Furthermore when $Ca(OH)_2$ reacts with the pozzolan the coarse space taken up by $Ca(OH)_2$ will be replaced with finer hydrates which would once again result in the strengthening of the microstructure of the cement paste (Robert, 1990). When Portland cement and water is used with pozzolans the initial strength gain of the microstructure and early setting is achieved due to the hydration reaction of Portland cement. At the initial stages the pozzolan behaves as an inert material. With time the rate of the hydration reaction of Portland cement will reduce and become insignificant whereas the pozzolanic reaction will become significant. Therefore in the latter stages the resultant hydrate products of the pozzolanic reaction will fill any capillary pores that were left empty after the hydration reaction of Portland cement and will occupy the space acquired by the coarse calcium hydroxide. Due to the replacement of a weaker coarser material as $Ca(OH)_2$ with a stronger finer material as C-S-H and due to the blocking and filling of large pores in the latter stages, the use of pozzolans to produce concrete has become a very famous concept in order to produce strong and impermeable concrete.

Hydration reaction of normal Portland cement,

$2C_3S + 6H \rightarrow C_3S_2H_3 + 3Ca(OH)_2$

$2C_2S + 4H \rightarrow C_3S_2H_3 + Ca(OH)_2$

The pozzolanic reaction ((Nastaranpoor, 2013), (Dabai, Muhammad, Bagudo & Musa, 2009)),

$3CH + 2SiO2 + 5H \rightarrow C_3S_2H_3$

There are many theories that explain the origin of the pozzolanic reaction. According to Reza et al., the presence of zeolites in the pozzolan is said to be the reason for it react with lime. Zeolites are alumina-silicate and micro porous minerals. It is said to have a wide range of cations which are loosely held by its structure hence it can easily attract or exchange with others in a contact solution. An ion replacement mechanism takes place during the reaction between the pozzolan and lime. The Dron theory can also be used to explain the pozzolanic reaction (Sersale, 1980). The base of this theory is the ability of feldspar shaped mineral to dissolve in a lime solution. Feldspar has a SiO_4 tetrahedra framework structure where all the corner oxygen's are been shared with the surrounding 'Si^{+4}'. When feldspar is dissolved in a lime solution the 'O' will get converted to an 'O^{-2}' ion where eventually it will convert to an 'OH^{-1}' ion (Sersale, 1980).

$2O^{-2} + 2H^{+1} \rightarrow 2(OH)^{-1}$

Therefore the released 'Si^{+4}' from feldspar will react with 'Ca^{+2}' ions in the lime solution and will form calcium silicate hydrates that would precipitate. When one silica unit gets released from the structure the next silica unit will be in contact with the lime solution and a similar mechanism would occur and will continue.

According to the Dron theory, pyroclastic pozzolans will undergo this mechanism much faster than other kinds due to the weak SiO_4 tetrahedra framework structure it has and zeolite pozzolans will also undergo this mechanism much faster due to its porous structure (Sersale, 1980).

2.3.4.3. *Microstructural Changes*

At the initial stages the total porosity of a pozzolanic paste is much greater than that of an ordinary Portland cement paste but in the latter stages the volume of capillary pores reduces while gel pore space ($< 75^{o}A$) increases in pozzolanic paste. According to Ogawa, Uchikawa, Takemoto and Yasui (1980), in some instances even the gel pore space reduces at later stages in a pozzolanic paste. This strengthens the microstructure of the cement paste, makes its pore structure finer and reduces the permeability of the cement paste (Manmohan & Mehta, 1981). According to a research conducted by Mehta et al., on pastes that contained various amounts of Santorin earth it was observed that the pozzolanic reaction can reduce the pore sizes greater than $1000^{o}A$. It was further stated that it mostly contained pores that were lesser than $100\ ^{o}A$. Hence Mehta et al., states that the strength increase in the paste can be ascribed to the size reduction of the pores due to the pozzolanic reaction (Manmohan & Mehta, 1981).

According to Masazza et al., there is said to be a strong correlation between the strength of the paste and the hydrated surface area and between the strength of the paste and the free $Ca(OH)_2$ content (Costa & Massazza, 1977). The latter relationship mainly depends upon the pozzolan been used (Costa & Massazza, 1977).

2.3.5. Changes in the Properties of Concrete When RHA is Added

2.3.5.1. The Changes That Occur in the Micro Structure of Concrete Paste That Contains RHA

According to many studies it can be seen that there are significant improvements in the mechanical and durability properties of concrete produced with partially replacing cement with RHA. It is achieved by a physical effect and a chemical effect (Ramezanianpour et al, 2009).

Physical effect

- Filler effect
  The fine RHA particles fill the spaces between the cement grains in the mortar as the cement particles fill the space between fine aggregates and fine aggregates fill the space between coarse aggregates. Due to this mechanism the mortar paste and the hardened concrete achieves a higher density and its porosity reduces. This effect can only be achieved if the RHA particles are ground to fineness lesser or equal to that of cement.
- The amount of coarse pores are reduced

As mentioned earlier due to the filler effect of RHA it reduces the amount of coarse pores present in the cement paste and transforms the interconnected pores in to discontinuous pores.

- A large number of nucleation sites are generated

  Due to the fine particles added a large area of nucleation sites will be created in order for the hydration products to get precipitated. It is stated by Ramezanianpour et al., that due to the large number of nucleation sites generated the reactions that occur will speed up and finer $Ca(OH)_2$ particles will be generated.

Chemical effect

It is mainly due to the pozzolanic reaction between the amorphous silica present in RHA and the $Ca(OH)_2$ released during the hydration reaction of cement. This reaction produces calcium silicate hydrates which get deposited in the pores present in the cement paste. Therefore a more dense cement paste can be achieved. This directly enhances the mechanical properties of concrete. Furthermore the amount of $Ca(OH)_2$ present in the cement paste reduces due to the pozzolanic reaction hence the durability of the hardened concrete increases.

2.3.5.2. Workability

The workability of concrete reduces due to the addition of RHA. According to Kartini et al., Rukzon et al., and Nagrale et al., it is mainly due to the absorptive cellular nature characteristic of RHA particles and its very fine particle size. A higher quantity of water is needed in order to achieve a good workable concrete. But it needs to be pointed out that when water added in to the mix is increased the strength of the hardened concrete tends to decrease. Therefore Kartini et al., suggests adding supper plasticizers in order to enhance the workability of the concrete mix. When the supper plasticizer is added in to the concrete mix it will be absorbed by the cement particles which will produce a strong negative charge. This will significantly reduce the surface tension imposed by the surrounding water; hence the fluidity of the mix will be significantly increased (Kartini, Mahmud & Hamidah, 2006).

2.3.5.3. Compressive Strength

According to many studies carried out in this area it is concluded that when RHA is used to replace cement to produce concrete the strength of the hardened concrete is initially very low at early ages of curing and with time it increases and in some cases can even be greater than that made with 100% ordinary Portland cement ((Ramasamy, 2011), (Kumar et al, 2012), (Ramezanianpour et al, 2009)). Furthermore when the percentage of RHA used to replace cement in the concrete paste increases the strength of the concrete reduces due the high water demand in order to achieve the designed workability ((Kumar et al, 2012), (Kartini et al, 2006)). Approximately 20-25% of ordinary Portland cement can be replaced with RHA without causing any changes in the strength of the concrete ((Kumar et al, 2012), (Godwin et al, 2013)). The percentage of cement replaced with RHA can be increased with the addition of super plasticizers in to the mix ((Ramasamy, 2011), (Kartini et al, 2006)).

2.3.5.4. Porosity

The porosity of concrete is a very vital parameter when discussing about the strength of concrete. When the capillary pores present in the concrete decreases the strength of the concrete increases. The porosity of the concrete paste reduces due to the packing effect of the fine RHA particles. Hence the volume and number of large pores present in the concrete paste will be reduced (Ramasamy, 2011).

2.3.5.5. Water Permeability

According to studies carried out in this area it is found out that with the incorporation of RHA in the cement paste the penetration of water in to the hardened concrete decreases with the age of curing. According to Nagrale et al., this phenomenon only occurs when RHA is finer than ordinary Portland cement. It is also stated that the water absorption of cement mortars made by partially replacing cement with RHA obtained from controlled burning is much lesser than that made with uncontrolled burning (Ramasamy, 2011).

2.3.5.6. Chloride Permeability

According to a study conducted by Ramezanianpour et al., it is stated that when the percentage of cement been replaced with RHA in the cement paste increases the amount of chloride ions that penetrates in to the concrete decreases. This is mainly due to the fact that when RHA is incorporated in to the cement paste a denser cement matrix and a finer pore structure is formed. Especially at the cement paste and aggregate interface. It becomes very difficult for the chloride ions to penetrate in to the concrete due to its fine pore structure. When the amount of cement been replaced with RHA is increased the chloride permeability of concrete can be reduced, thereby increasing its durability and preventing corrosion from occurring. It is further reported by Ramezanianpour et al., that by replacing 10-15% of cement with RHA the resistance the concrete has against chloride permeability can be increased.

2.3.5.7. Effect of Rice Husk Ash on Acid Attack

When acid penetrates in to the hardened concrete the calcium compounds (mainly $Ca(OH)_2$) present in the mortar paste will react with it and form calcium salts of it. For example if hydrochloric acid penetrates in to hardened concrete it will react with $Ca(OH)_2$ preset in the mortar and will form calcium chloride ($CaCl_2$). Due to the acid attack the concrete gets deteriorated and its durability is reduced.

According to Mehta et al., concrete that was produced by partially replacing cement with RHA has a higher resilient to acid attack than that made with 100% of cement. There is a significant reduction in the permeability of the hardened concrete due to the fine cement matrix produced when RHA is used to produce concrete. The pozzolanic reaction between RHA and $Ca(OH)_2$ produces C-S-H which makes the cement matrix in the hardened concrete more denser and stronger furthermore it reduces the amount of $Ca(OH)_2$ available in the cement pastes. Thereby increasing the acid resistance of the concrete produced with RHA ((Ramasamy, 2011), (Mehta, 1992)).

2.3.5.8. Effect of Rice Husk Ash on Sulphate Resistance

The sulphate attack of hardened concrete is mainly caused due to the chemical reaction between $Ca(OH)_2$ present in the paste and the sulphate that penetrated in to the concrete. Salts in ground water, sewage industrial waste and seawater are some of the sources of sulphate ions. Gypsum is formed due to this chemical reaction and will react with Tricalcium aluminate (C_3A) present in the mortar and will produce ettringite and monosulphoaluminate which will be detrimental to the durability of concrete. The ettringite and monosulphoaluminate present in the paste will then cause the volume of the concrete to expand which will lead to undesirable cracking and peeling off of the hardened concrete. The pozzolanic reaction between RHA and $Ca(OH)_2$ produces C-S-H which makes the cement matrix in the hardened concrete more denser and stronger furthermore it reduces the amount of $Ca(OH)_2$ available in the cement pastes. Thereby the concrete produced using RHA has a high sulphate resistance (Ramasamy, 2011).

Chapter 03:EXPERIMENTAL INVESTIGATION

3.1. Main Types of Raw Materials Used in the Research and Their Specific Preparations

3.1.1. Aggregates

3.1.1.1. Coarse Aggregates

The main types of coarse aggregates used in this research were natural coarse aggregates (NCA) and recycled coarse aggregates (RCA).

Locally available ¾” size natural aggregates which is commonly used in construction, was used as the NCA.

RCA was obtained from the COWAM center located at Dadalla, Galle. The RCA size fraction that was obtained from the COWAM center was of the ¾” size fraction.

3.1.1.2. Fine Aggregates

River sand was used as the fine aggregates in this research study.

3.1.2. Rice Husk Ash (RHA)

Six RHA samples were obtained from various rice mills that undergo the parboiling process of rice in the Polonnaruwa and Ampara districts. Four samples were obtained from the Polonnaruwa district and 2 samples were obtained from the Ampara district.

The RHA that were obtained had a coarse texture; hence they were ground by the Los Angeles abrasion testing machine. The grinding was carried out for a given number of revolutions (1500 revolutions) at a speed of 30 revolutions per minute (30 rpm).

3.1.3. Lime and Cement

Lime was purchased from the locally available hardware store.

Holcim ready flow cement having strength class of 42.5 N/mm^2 was used.

3.2. Initial Testing Conducted on the Raw Materials

Main objective of this research study was to treat the porous surface of RCA by coating it with a RHA- Lime slurry or RHA- Cement slurry. Hence the aggregate properties of untreated RCA and NCA were tested to check the compatibility of RCA with NCA, hence proving the need to treat the surface of RCA in order for it to be used as a replacement for NCA. The basic physical and chemical properties of the RHA samples were tested in order to check their material composition and properties, to select the best RHA sample for the experimental investigation.

3.2.1. Coarse Aggregates

To determine the properties of untreated RCA and NCA, following tests were carried out in accordance with the relevant specifications indicated.

- Particle size distribution test - (BS-812-103.1, 1985)
- Specific Gravity and Water Absorption test - (BS 812: Part 2: 1975)
- Bulk Density test - (BS 812: Part 2: 1975)
- LAAV test for crushing and impact value of aggregates- (ASTM C131)
- AIV test for impact value of aggregates - (IS: 2386 part IV)

3.2.1.1. Particle Size Distribution Test

The particle size distribution of aggregates was obtained from sieve analysis conducted in accordance with the BS-812-103.1, 1985. The dry sieving method was followed in this analysis. The test apparatus that were used in this test are given in Appendix - A.

3.2.1.1.1. Sample Preparation for Particle Size Distribution Test

To analyze the particle size distribution a sufficient mass of the sample should be obtained. According to the standard the minimum mass of a sample needed to be obtained according to its maximum particle size is shown in Table 3.1. Since the maximum particle size of the coarse aggregates used in this study was 20 mm, a mass of 2 kg was used in this analysis.

Table 3.1: Minimum Mass Required According to the BS- Standard Code

Maximum particle size (mm)	**63**	**50**	**40**	**28**	**20**	**14**	**10**	**6**	**5**	**3**	**< 3**
Minimum mass main sample (kg)	50	35	15	5	2	1	0.5	0.2	0.2	0.2	0.1

Before conducting the test the coarse aggregates had been oven dried at a temperature of 105 ± 5^{o}C for a minimum time of 12 hours. To obtain the required mass and a well divided sample, a divider had been used.

3.2.1.1.2. Basic Steps of the Particle Size Distribution Test

- The selected sieves were stacked one on top of the other according to a descending order, where the sieve with the largest opening size was placed on top and the sieve with the smallest opening size was placed at the bottom
- A pan was placed at the bottom most level of the sieve set
- A well washed and oven dried coarse aggregate sample (i.e. RCA or NCA) having a known weight was poured onto the top most sieve
- Afterwards the sieve set was covered by a lid and shaken by using a mechanical sieve shaker until there were no more aggregates passing each sieve
- Each sieve was hand shaken to make sure that the separation was complete
- Afterwards the mass retained on each sieve was weighed with an electronic balance

3.2.1.2. Specific Gravity and Water Absorption Test

The specific gravity and water absorption test was conducted with accordance to the BS 812: Part 2: 1975. The test apparatus that were used in this test are given in Appendix - A.

3.2.1.2.1. Sample Preparation of the Specific Gravity and Water Absorption Test

A sample of around 1 kg of the aggregate was used. The sample was thoroughly washed on the 5 mm test sieve so that the finer particles such as dust, silt and clay were removed and drained. The washed aggregates were then placed on a clean tray and fresh water was added so that the aggregate sample was completely immersed in water. The sample was then kept to soak for a time period of 24 ± 0.5 hours.

3.2.1.2.2. Basic Steps of Specific Gravity and Water Absorption Test

- The test sample was then transferred in to the glass vessel that had a sufficient amount of water so that the aggregate sample could be completely immersed in it
- Afterwards the vessel was gently agitated to remove entrapped air
- The vessel was overfilled by adding water and the plane ground glass disk was slipped over the mouth of the vessel so that to make sure that no entrapped air exists in the vessel
- Then the vessel was dried and weighed (mass B)
- Afterwards the vessel was emptied and the aggregate sample was allowed to drain, at the mean time the vessel was refilled with water and the glass disk was slipped in to place as before
- The vessel was then dried and weighed (mass C)
- The aggregates were then placed on a dry cloth and the surface of the aggregates were gently dried by it
- The aggregates were then spread out not more than one stone deep on the second dry cloth and was left to be exposed to air away from direct sunlight until all visible films of water were removed, but it needs to be taken in to consideration that the aggregate still needs to have a damp appearance that is it needs to be in its surface saturated dry (SSD) condition
- The aggregates were then weighed (mass A)
- The aggregates were then placed in a shallow tray and placed in an oven to dry at 105^{o}C for 24 ± 0.5 hours

- The sample was then cooled in the airtight container and weighed (mass D)

3.2.1.3. Bulk Density Test

The bulk density test was conducted in accordance with the BS 812- Part 2-1995. The test apparatus that were used in this test are given in Appendix - A.

3.2.1.3.1. Preparation of Samples for the Bulk Density Test

The aggregate sample that passed through a 40mm sieve and retained on a 4.75mm sieve was used in this test. The specific size fraction of the sample was washed and oven dried at a temperature of 105 ± 5^{o}C for 24 ± 0.5 hours.

3.2.1.3.2. Basic Steps of the Bulk Density Test

- The empty calibrating container having a volume of 15 liters was weighed (mass m1)
- Afterwards the prepared sample of aggregates was put in to the container in three layers
- In order to compact the aggregates so that to remove excessive room in the container each layer was given 25 blows with the tamping rod
- After compacting the aggregates in three layers the excess aggregates were removed by leveling the calibrating container
- The weight of the calibrating container that was filled with well compacted aggregates was weighed (mass m2)
- The aggregates were then removed from the calibrating container and it was filled again with the aggregate sample without any tamping been done
- The excess aggregates were removed from the calibrating container by leveling it and the container was weighed (mass m3)

3.2.1.4. Los Angeles Abrasion Value (LAAV) Test

The Los Angeles abrasion value (LAAV) test was conducted in accordance with the ASTM C 131: 89. The test apparatus that were used in this test are given in Appendix - A.

3.2.1.4.1. Preparation of Samples for LAAV Test

The test sample was washed and oven dried at 105^{o}C to 110^{o}C until a fairly constant mass was gained. The sample was then separated into individual size fractions according to grade B given in Table 3.2, and had been recombined. The mass of the graded sample was then weighed to the nearest 1g (mass m1).

3.2.1.4.2. Basic Steps Involved With LAAV Test

- The test sample and the charge were placed in the Los Angeles testing machine and were rotated for 500 revolutions at a speed of 30 rpm
- Afterwards the material was discharged and sieved by a 1.70 mm sieve
- The material coarser than 1.70 mm sieve was washed
- The washed coarse material was then oven dried at 105^{o}C to 110^{o}C until a fairly constant mass and was weighed to the nearest 1 g (mass m2)

3.2.1.5. Aggregate Impact Value (AIV) Test

The aggregate impact value (AIV) test was conducted in accordance with the BS 812: Part 112: 1990. The test apparatus that were used in this test are given in Appendix - A.

3.2.1.5.1. Preparation of Samples for AIV Test

The test sample was reduced to produce a sufficient mass according to Table 3.3, so that to produce three test specimens of 14 mm to 10 mm size fraction. The entire dried test portion was sieved on the 14 mm and 10 mm sieves so that the oversized and undersized size fractions were removed. The resulting 14 mm and 10 mm size fraction was divided to produce two test specimens each of sufficient mass so that the entire cylindrical metal measure can be filled. The test specimens were then oven dried at 105 ± 5^{o}C for not more than 4 hours and were cooled afterwards. The metal measure was then filled to overflow with aggregates. The aggregate were then tamped with 25 evenly distributed blows with the rounded end of the tamping rod. To give each blow the tamping rod was let to free fall from a height of 50 mm above the surface of the aggregate. The surplus aggregates were removed by rolling the tamping rod across the container. The aggregates that impede the movement of the tamping rod were removed and the clearly seen depressions were filled with aggregates. The net mass of the aggregate in the cylindrical measure was recorded and the same mass was used for the second test specimen.

Table 3. 2: The Minimum Mass of Test Samples Required to Determine AIV

Grade of the Aggregate (Mm)	Minimum Mass of the Test Portion (Kg)
All- in Aggregate 0- 40 Mm Max. Size	20
All- in Aggregate 0- 20 Mm Max. Size	15
Graded Aggregate 40 To 5 Mm	12
Graded Aggregate 20 To 5 Mm	8
Graded Aggregate 14 To 5 Mm	5

3.2.1.5.2. Basic Steps Involved With AIV Test

- The test specimen was placed in the cup fixed in the impact machine and was compacted by giving 25 strokes with the tamping rod. The height of the hammer was adjusted so that it was 380 ± 5 mm above the upper surface of the aggregate in the cup
- The hammer was then let to fall freely on to the aggregate to achieve a total of 15 blows at intervals of not less than 1 s
- The crushed aggregate was removed by placing the cup over a clean tray and hammering on the outside with the rubber mallet until the particles were sufficiently loose to enable the specimen to fall freely on to the tray. A brush was used to remove the fine particles attached to the inside of the cup and the underside of the hammer
- The mass of the aggregate was weighed and recoded to the nearest 0.1 g (mass m1)

- The entire specimen was then sieved through a 2.36 mm sieve until no further significant amount had passed
- The mass of the fraction passed and retained on the 2.36 mm sieve were weighed and recorded to the nearest 0.1 g (mass m2 and mass m3 respectively)
- The procedure was repeated with a second specimen of the same mass as the first specimen

3.2.2. Rice Husk Ash (RHA)

3.2.2.1. Chemical Testing

3.2.2.1.1. Loss on Ignition

The loss on ignition of the RHA samples were tested in accordance with the BS 4550: Part 2: 1970. All details of this test is given in Appendix - A.

3.2.2.1.2. Total Silica Present in the RHA Sample

The total silica present in the RHA sample was tested according to the methodology given in the Vogel's text book of quantitative chemical analysis (5th edition) that is in compliance with the BS 4550: Part 2: 1970, on the determination of silica in soluble silicate form and insoluble silicate form. All details of this test is given in Appendix - A.

3.2.2.1.3. Al_2O_3 and CaO Present in the RHA Sample

Al_2O_3 and CaO present in the RHA sample was tested according to the methodology given in the Vogel's text book of quantitative chemical analysis (5th edition) and the methods manual (Issue 3) of Atomic Absorption Spectrometry printed by Thermo Elemental. All details of this test is given in Appendix - A.

3.2.2.2. Physical Testing

3.2.2.2.1. Particle Density Determination

The particle density determination was conducted in accordance with the BS 1377: Part 2: 1990. All details of this test is given in Appendix - A.

3.2.2.2.2. Particle Size Distribution Test

The particle size distribution test was conducted in accordance with the BS 812: Part 103.1: 1985 and BS 1377: Part 2: 1990. The dry sieving method was followed in this analysis.

The particle size distribution analysis of the six RHA samples were each conducted for two stages. That is before grinding and after grinding each RHA sample. As mentioned earlier the RHA sample was ground by the Los Angeles abrasion testing machine. The grinding was carried out for a given number of revolutions (1500 revolutions) at a speed of 30 revolutions per minute (30 rpm).

In order to trigger the pozzolanic property of RHA its average particle size needs to have a fineness that is of cement or lesser. Hence the effectiveness of using a Los Angeles abrasion testing machine to grind the RHA particles to achieve the needed fineness was another key factor tested in this section.

All details of this test is given in Appendix - A.

3.2.2.3. Selecting the Best RHA Sample

In order for RHA to act as a good pozzolan it needs to have a substantial amount of amorphous silica (SiO_2) present in it. When selecting the best RHA sample for the work needed to be carried out in the future a much weight was given to the amount of amorphous silica (SiO_2) present in the RHA sample. The results obtained from the chemical testing and physical testing of the RHA samples were analyzed and the most suitable RHA sample was selected from the six RHA samples that were tested.

3.3. Surface Treatment Methods Used

The main objective that needed to be achieved in this study was to enhance the porous surface of RCA by impregnating the pores with fine particulates. The fine particulates used in this study were RHA that represented a pozzolan material, cement and lime that was used as the binding agents. The RCA was coated by a slurry consisting varying fractions of fine materials (i.e. RHA, cement and lime) with varying fractions of water to treat the surface of the RCA.

The slurry used to treat the surface of RCA consist a solid composition and a liquid composition. In the slurry the solid composition was mainly a mixture of ground RHA and lime or ground RHA and cement. The liquid composition in the slurry was water. The scenarios of slurry ratios that were used to coat RCA is more clearly given in Table 3.6 and Table 3.7. The RCA was treated with various slurry ratios by varying the liquid composition in the slurry in order to identify the best slurry ratio that can be used to treat the surface of RCA according to the surface treatment method used in the current study. Furthermore the solid composition of each slurry ratio used in the study was varied in order to identify the best solid composition that can be used to treat the surface of RCA according to the surface treatment method used in the current study.

A mixer having a capacity of 90-136 liters was used to coat the RCA with various slurry ratios having varying solid compositions. Firstly the slurry was put into the mixer and was let to mix for 2 minutes, afterwards the RCA was placed in the well mixed slurry and the mixer was again left to rotate for 10 minutes. Then the coated RCA was removed from the mixer and was placed on a wire mesh so that to remove the excess slurry and to air dry it for 24 hours.

3.3.1. Scenarios of Ground Rice Husk Ash (RHA) - Lime Slurry Used to Coat RCA

As the first treatment method, ground RHA and lime mixed with water in different ratios were used to coat the RCA. Four main slurry ratios (i.e. liquid: solid) were used by varying the amount of liquid added to the slurry. The slurry ratios used to coat RCA varied from 0.625, 0.750, 0.875 and 1.000. Furthermore for each slurry ratio, the RHA to lime composition of the solid component of the slurry was varied as 20%: 80%, 40%: 60%, 50%: 50%, 60%: 40% and 80%: 20% respectively. The RHA- lime slurry scenarios that were used in the current study are given in Table 3.6.

Table 3. 3: RHA- Lime Slurry Scenarios Used in the Current Study

		Slurry Ratio (Liquid: Solid)			
RHA (%)	Lime (%)	0.625	0.750	0.875	1.000
20	80	√	√	√	√
40	60	√	√	√	√
50	50	√	√	√	√
60	40	√	√	√	√
80	20	√	√	√	√

Note: √- scenarios that had been used to coat RCA

3.3.2. Scenarios of Ground Rice Husk Ash (RHA) - Cement Slurry Used to Coat RCA

As the second treatment method, ground RHA and cement with water in different ratios were used to coat the RCA. In this case eight main slurry ratios (i.e. liquid: solid) were used by varying the amount of water added to the slurry. The slurry ratios used to coat RCA were 0.625, 0.750, 0.875, 1.000, 1.250, 1.500, 1.750 and 2.000. Furthermore for each slurry ratio, the RHA to cement composition of the solid component of the slurry was varied as 0%: 100%, 20%: 80%, 40%: 60%, 50%: 50%, 60%: 40% and 80%: 20% respectively. The RHA- cement slurry scenarios that had been used in the current study are given in Table 3.7.

Table 3. 4: RHA- Cement Slurry Scenarios Used in the Current Study

		Slurry Ratio (Liquid: Solid)							
RHA (%)	Cement (%)	0.625	0.750	0.875	1.000	1.250	1.500	1.750	2.000
0	100	🟩 √	🟩 √	🟩 √	🟩 √	🟥 √	🟥 √	🟥 √	🟥 √
20	80	🟩 √	🟩 √	🟩 √	🟩 √				
40	60	🟩 √	🟩 √	🟩 √	🟩 √				
50	50	🟩 √	🟩 √	🟩 √	🟩 √				
60	40	🟩 √							
80	20	🟩 √							

Note: √ - Scenarios that had been used to coat RCA

🟩- The specific gravity and water absorption of the coated RCA and the mortar strength of the slurry had been tested

🟥- The water absorption of the coated RCA had been tested

3.3.3. Testing Carried Out on Treated Recycled Coarse Aggregate (TRCA)

The tests carried out for the coated RCA and the slurry used to coat the RCA is described in this section.

The main aim of the study was to reduce the high water demanding property of RCA by coating and impregnating the porous surface of RCA with slurry containing fine particulates of RHA and lime or cement thereby enhancing the physical properties of RCA. Hence the specific gravity and water absorption capacity ((BS 812: Part 2: 1975)) were the only aggregate properties that were analyzed of the coated RCA.

If the coating of the RCA is not properly bonded to the porous surface of the RCA it can easily break off when used in a concrete mix, hence causing negative impacts to the strength factor of the concrete. To get an understanding of the strength of the slurry used to coat the RCA, mortar cubes having the dimensions of 50 mm X 50 mm X 50 mm were made with only the slurry and their strengths were tested for varying curing ages (BS 4551: Part 1: 1970).

3.3.3.1. Specific Gravity and Water Absorption of the Coated RCA

The specific gravity and water absorption test was conducted in accordance with the BS 812: Part 2: 1975. The test apparatus that were used in this test are given in Appendix - A.

3.3.3.1.1. Sample Preparation of the Specific Gravity and Water Absorption Test

3.3.3.1.1.1. Samples Coated With a RHA- Lime Slurry

An air dried sample of around 1 kg of the coated RCA was used. The sample was thoroughly washed on the 5 mm test sieve so that the finer particles such as dust, silt and clay was removed and drained. The washed aggregates then were placed on a clean tray and fresh water was added so that the coated aggregate sample was completely immersed in water. The sample then was kept to soak for a time period of 24 ± 0.5 hours.

3.3.3.1.1.2. Samples Coated With a RHA- Cement Slurry

An air dried sample of around 3- 5 kg of the coated RCA was used. The sample was thoroughly washed on the 5 mm test sieve so that the finer particles such as dust, silt and clay was removed and drained. The washed aggregates then were placed inside a clean polythene bag that was labeled according to the coating scenario used and the bag was tied. The bag containing the coated RCA then was immersed in the curing tank so that the coated RCA sample was completely immersed in water. It should be noted that the tied knot of the bag should allow the water to enter in to it, but should not let the aggregates escape from it. The samples were kept to cure for 3 days, 7 days, 14 days and 28 days as clearly shown in Table 3.8.

Table 3. 5: RHA- Cement Slurry Scenarios Used in the Current Study

		Slurry Ratio (Liquid: Solid)							
RHA (%)	Cement (%)	0.625	0.750	0.875	1.000	1.250	1.500	1.750	2.000
0	100	🟩 √	🟩 √	🟩 √	🟩 √	🟥 √	🟥 √	🟥 √	🟥 √
20	80	🟩 √	🟩 √	🟩 √	🟩 √				
40	60	🟩 √	🟩 √	🟩 √	🟩 √				
50	50	🟩 √	🟩 √	🟩 √	🟩 √				
60	40	🟩 √							
80	20	🟩 √							

Note: √ - Scenarios that had been used to coat RCA

🟩- The specific gravity and water absorption of the coated RCA had been tested

🟥- The water absorption of the coated RCA had been tested

3.3.3.1.2. Basic Steps of Specific Gravity and Water Absorption Test

- An appropriate amount of the test sample was then transferred in to the glass vessel that had a sufficient amount of water so that the aggregate sample could have been completely immersed in it
- Afterwards the vessel was gently agitated to remove entrapped air
- The vessel was overfilled by adding water and the plane ground glass disk was slipped over the mouth of the vessel so that to make sure that no entrapped air exists in the vessel
- Then the vessel was dried and weighed (mass B)
- Afterwards the vessel was emptied and the aggregate sample was allowed to drain, at the mean time the vessel was refilled with water and the glass disk was slipped in to place as before
- The vessel was then dried and weighed (mass C)
- The aggregate was then placed on a dry cloth to gently surface dry it with the cloth

- The aggregate was then spread out not more than one stone deep on the second dry cloth and it was left to be exposed to air away from direct sunlight until all visible films of water was removed, but it needs to be taken in to consideration that the aggregate still needs to have a damp appearance that is it needs to be in its surface saturated dry (SSD) condition
- The aggregates were then weighed (mass A)
- The aggregates then were placed in a shallow tray and placed in an oven to dry at 105°C for 24 ± 0.5 hours
- The sample then was cooled in the airtight container and weighed (mass D)

3.3.3.2. Determination of Strength of Each Slurry Scenario

To get an idea of the strength of the slurry used to coat the RCA, mortar cubes made up with only the slurry having the dimensions of 50 mm X 50 mm X 50 mm were cast and their strengths were tested in accordance with the BS 4551: Part 1: 1970.

The RHA- lime slurry scenarios that were used to make mortar cubes in the current study is shown in Table 3.9. The mortar cubes were cured for 28 days and the effect on the variation of mortar strength due to varying slurry ratios having varying RHA: lime ratios were tested. It should be noted that for each scenario of slurry, 3 mortar cubes were made.

Table 3. 6: RHA- Lime Slurry Scenarios Used to Make Mortar Cubes

		Slurry Ratio (Liquid: Solid)			
RHA (%)	Lime (%)	0.625	0.750	0.875	1.000
0	100	√	√	√	√
20	80	√	√	√	√
40	60	√	√	√	√
50	50	√	√	√	√
60	40	√	√	√	√
80	20	√	√	√	√

Note: √- scenarios that had been used to make mortar cubes

The RHA- cement slurry scenarios that were used to make mortar cubes in the current study is shown in Table 3.10. The mortar cubes were cured for 7 days, 14 days and 28 days and the effect on the variation of mortar strength due to varying slurry ratios having varying RHA: cement ratios were tested. It should be noted that for each scenario of slurry and for each age of curing, 3 mortar cubes were made.

Table 3. 7: RHA- Cement Slurry Scenarios Used to Make Mortar Cubes

		Slurry Ratio (Liquid: Solid)			
RHA (%)	Cement (%)	0.625	0.750	0.875	1.000
0	100	√	√	√	√
20	80	√	√	√	√
40	60	√			
50	50	√			
60	40	√			
80	20	√			

Note: √ - Scenarios that had been used to make mortar cubes

3.3.3.2.1. Batch Proportioning of Material Needed to Make The Mortar Cubes

The calculations that were carried out to find out the mass of the materials that were needed to make the mortar cubes are shown in Table 3.11.

Table 3. 8: Calculations That Had Been Carried Out to Make the Mortar Cubes

The volume of a mortar cube	**= 5 X 5 X 5 cm^3** **= 125 cm^3**
A buffer of one extra cube had been included to the total amount of cubes needed to be made. **That is,** - **For the RHA- lime slurry: the calculations had been made for 4 cubes** - **For the RHA- cement slurry: the calculations had been made for 10 cubes**	
Hence the total number of mortar cubes that had been made including the extra cube	= n
That is, - **For the RHA- lime slurry: n= 4** - **For the RHA- cement slurry: n= 10**	
Hence the total volume of mortar cubes that had been made including the extra cube	= n X 125 cm^3
Assume the density of water is	=1gcm^{-3}
Therefore the water required to make the mortar cubes	= n X 125 X 1 g = W_{water} g
The slurry ratio (liquid: solid)	= z
Hence the total mass of the solid content (i.e. RHA+ lime/ cement) needed	= W_{water}/z g = W_{solid} g
If the RHA- lime/cement ratio is	= p: q (%: %)
Hence the total mass of RHA needed to make the mortar cubes	= W_{solid}X (p/100) = W_{RHA} g
Hence the total mass of lime/cement needed to make the mortar cubes	= W_{solid}X (q/100) =$W_{lime/cement}$ g

The test method that was used to prepare the mortar cubes are given in Appendix - A.

3.3.3.2.2. Curing

- The specimens were stored at a place free from vibration under damp sacks and were covered completely with polythene at a temperature of 20 ± 5°C for 1 to 3 days depending on the early strength of the slurry (i.e. until the slurry cubes are well set)
- They were then removed from the moulds and marked for future identification
- Afterwards they were stored in clean water until the time of test. The temperature of the storage water was maintained within the range of 20 ± 2°C.

3.3.3.2.3. Determination of Compressive Strength

- The specimen was tested immediately on removal from the curing water where it was stored and whilst it was in a wet condition
- The dimensions of the specimen was noted before testing
- The bearing surfaces of the testing machine was wiped clean and the specimen was placed in the machine in such a manner that the load was applied to the verticle sides of the cube as casted, that is not to the top or bottom
- The axis of the cube was carefully aligned with the center of thrust of the spherically seated platen
- No packing other than auxiliary steel plates were used between the faces of the specimen and the steel platen of the testing machine
- As the spherically seated block was brought to bear on the specimen, the movable portion was gently rotated by hand in order to obtain uniform seating
- The load on the specimen was applied without shock and at a uniform rate within the range of 2N/mm^{2}per min. to 6N/mm^{2}per min. until failure had occurred

3.3.4. Selecting the Best Surface Treatment Method

Specific gravity and water absorption test results of various coated RCA and the mortar cube strength test results of the various slurry ratios were analyzed and the best surface treatment method for RCA was selected.

Comparing the test results obtained when RHA- lime slurry was used as the surface treatment method for RCA, it showed an inferior effect when comparison to the RHA- cement slurry that was used as the surface treatment method. Furthermore the strength of the coating when RHA-lime slurry was used is very much lesser than when the RHA- cement slurry was used. Hence the RHA- cement slurry was selected over that of RHA- lime slurry to coat the RCA.

When considering the specific gravity and water absorption of coated RCA that was coated with RHA- cement slurry, three main parameters were varied. They were the slurry ratio, RHA: cement ratio and the curing age. Hence to select the best coating method the best slurry ratio, the best RHA: cement ratio and the best curing age had to be known. By analyzing the data obtained from the specific gravity and water absorption of coated RCA the following conclusions were made,

- When RHA: cement is 0%: 100% the best slurry ratio (liquid: solid) that should be used to coat RCA in order for its high water absorption capacity to be reduced is 1.500
- Cement can be replaced up to 40% with RHA in the solid composition of the slurry used to coat RCA so that its high water absorption capacity can be reduced
- When RHA: cement is 20%: 80% or 40%: 60% the best slurry ratio (liquid: solid) that should be used to coat RCA in order for its high water absorption capacity to be reduced is 0.875
- The best curing age that gives the lowest water absorption capacity of coated RCA is 7 days

It should be pointed out that a more elaborate explanation on how the best surface treatment method was selected is given in the results and discussion section.

3.4. Testing of Concrete Specimens

Concrete was made with NCA, untreated RCA and the selected special scenarios of coated RCA. Concrete was made with NCA and untreated RCA in order to compare the results obtained when concrete was made with the selected treated RCA.

3.4.1. Scenarios of Concrete Specimens

The scenarios of coarse aggregates (i.e. NCA, RCA and treated RCA) that were used to make the concrete specimens are given in Table 3.12 and Table 3.13. The RCA that was treated with the scenarios shown in Table 3.12 were cured for 7 days. The RCA that was treated with the scenarios shown in Table 3.13 was cured for 24 hours. All types of coarse aggregates that were used to make concrete were at their surface saturated dry (SSD) condition. For the scenarios shown in Table 3.12, three cubes each having the dimensions of 150 mm X 150 mm X 150 mm were made and were cured for 28 days. For the scenarios shown in Table 3.13, three cubes each having the dimensions of 150 mm X 150 mm X 150 mm were made and were cured for 28 days.

Table 3.9: Scenarios of Coarse Aggregates Used to Make the Concrete Specimens

Type of Coarse Aggregate	Slurry Ratio (Liquid: Solid)	RHA: Cement
NCA	-	-
RCA	-	-
Treated RCA	1.500	0: 100
	0.875	20: 80
		40: 60

Table 3. 10: Scenarios of Treated RCA that had been used to make the Concrete Specimens

RHA (%)	**Cement (%)**	**Slurry Ratio (Liquid: Solid)**			
		0.625	0.75	0.875	1.00
0	100	√	√	√	√
20	80	√	√	√	√

Note: √ - Scenarios that had been used to make mortar cubes

3.4.2. Making of Concrete

3.4.2.1. Mix Design

The DoE mix design method was used to design the appropriate mix proportions needed to make the concrete.

The main requirements to be specified in this method are,

- Characteristic compressive strength (and % defective)
- Cement strength class
- Slump
- Maximum aggregate size
- Maximum free water/cement ratio (w/c ratio)
- Maximum cement content
- Minimum cement content

The calculations that were carried out to obtain the mix proportions needed to make the concrete are shown in Apendix - B.

Hence the proposed mix design to make a concrete having a specified characteristic strength of 30 N/mm2 with a w/c ratio of 0.55 is,

- Water = 205 kg/m3

- Cement = 372.73 kg/m3

- Fine aggregates = 891.61 kg/m3

- Coarse aggregates = 937.33 kg/m3

3.4.2.2. Making Test Cubes from Fresh Concrete

The making of test cubes from fresh concrete was carried out in accordance with the BS 1881: Part 108: 1983. Details are given in Appendix – A.

3.4.3. Testing Conducted on Fresh and Hardened Concrete

3.4.3.1. Testing Conducted on Fresh Concrete

3.4.3.1.1. Slump Test

The slump test was conducted in accordance with the BS 1881: Part 102: 1983. Details are given in Appendix – A.

3.4.3.2. Testing Conducted on Hardened Concrete

3.4.3.2.1. Compressive Strength Test

The compressive strength of the concrete cubes was tested in accordance with the BS 1881: Part 116: 1983. Details are given in Appendix – A.

Chapter 04:RESULTS AND DISCUSSION

4.1. Test Results Obtained From the Initial Testing Conducted on the Raw Materials

4.1.1. Coarse Aggregate

4.1.1.1. Particle Size Distribution Test Results of Recycled Coarse Aggregates (RCA) and natural coarse aggregates (NCA)

According to the particle size distribution curve shown in Figure 4.1, the effective sizes related to 10%, 30% and 60% passing, coefficient of uniformity (Cu), coefficient of curvature (Gradation) (Cc) of NCA and RCA are shown in Table 4.1.

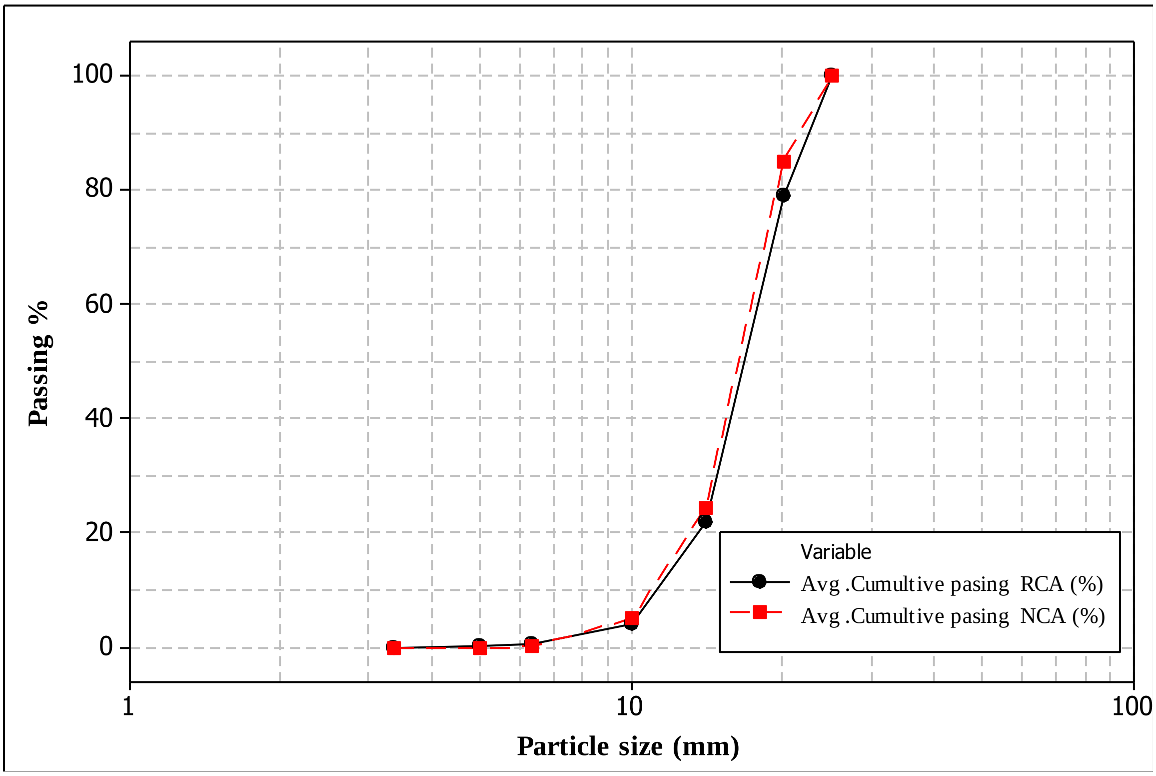


Figure 4. 1: Particle Size Distribution Ccurve of Natural Coarse Aggregate (NCA) and Recycled Coarse Aggregate (RCA)

Table 4. 1: Particle Size Distribution for NCA and RCA

		Critical Particle Sizes (mm)		
			NCA	RCA
Passing Percentage (%)	10	D10	11.03	11.31
	30	D30	14.56	14.85
	50	D50	16.54	16.95
	60	D60	17.53	18.00
Coefficient of Curvature (Gradation) (Cc)			1.0961	1.0841
Coefficient of Uniformity (Cu)			1.5900	1.5917

The main objective of carrying out a sieve analysis is to divide an aggregate sample in to portions that will each contain particles of similar sizes (Neville, 2011). An aggregate sample that has a good gradation will produce concrete that has a good workability. The workability has an influence on the amount of water and cement required, it controls segregation; it effects the bleeding of fresh concrete and affects the placing and finishing of concrete. It should be pointed out that the strength characteristic of a well compacted concrete that has a fixed water-cement ratio does not depend upon the grading of the aggregate. To achieve the design strength given for a specific water-cement ratio the concrete needs to be well compacted. Only a workable mix can be fully compacted. On the other hand the gradation of an aggregate has an indirect effect on the strength characteristic of a well compacted concrete that has a fixed water-cement ratio. The gradation of aggregates is important to determine the surface area of it, the specific volume obtained by it and its tendency to segregate.

The amount of water needed to wet all the coarse aggregate particles mainly depends upon its surface area. According to Neville (2011) the overall specific surface and the grading of an aggregate is related to one another. This is said to exhibit a nonlinear relationship. That is if the gradation of an aggregate is in the range of large particle sizes the overall specific area is said to reduce thereby the water requirement of it also reduces. In a mix design the strength is mainly highlighted when calculating the water-cement ratio. To make a good concrete the surface of the aggregate particles need to be covered with the fresh cement mortar. Hence when the surface area of the aggregate is less the fresh cement mortar needed to cover its surface is less hence less water is required. On the contrary according to Neville (2011) for aggregate particles that demonstrate a wide range of aggregate grading (i.e. gap graded or continuously graded) that has the same specific area; the water requirement and the compressive strength of the concrete are the same. When comparing RCA with NCA we see that its surface area increases due to the attached mortar on its surface. The surface area of an aggregate is an essential parameter when considering the workability of a concrete mix.

The segregation of aggregates in a concrete mix and the workability of a concrete mix is said to be partially contrary to one another. The smaller particles can easily pass through in to the voids made between the larger particles. On the contrary these smaller particles can be easily shaken out from the voids causing segregation. A concrete mix with a good workability can produce an economical and strong concrete but if segregation occurs in concrete honeycombing, weak and concrete that is not durable will be produced. The prevention of the fresh cement paste from passing through the voids created between the coarse particles is what is very essential for the concrete to be satisfactory; hence these voids need to be sufficiently small in size (Neville, 2011).

When the aggregate particles are graded in order to achieve the maximum density the concrete made by it can turn in to a somewhat harsh and unworkable mix. Neville (2011) states that in order to improve the workability of a concrete there needs to be an excess amount of cement paste that will fill the voids between the sand particles and an excess quantity of mortar (i.e. cement paste and the fine aggregate) that will fill the voids between the coarse aggregates.

As shown in Figure 4.2, there are four types of gradation categories been used in the industry to describe the particle size distribution curve of aggregates. They are,

- Dense or well graded: In a gradation if the particle sizes present are represented by equal amounts of particles it is known as a dense gradation. Therefore the air voids present between the particles can be reduced. The curve represented by the dense gradation is an even curve. An aggregate sample that has this type of gradation can produce a well packed structure hence it is a very desirable type of gradation when making concrete.
- Gap graded: It refers to a type of gradation where one or more middle size fractions are present in a small percentage or are been omitted. The gradation curve is generally flat in the intermediate size range. In this type of gradation if many middle sizes are missing, segregation during placement of concrete could occur ((Pavement Interactive, 2011), (Neville, 2011)). When the

needed workability of the fresh concrete mix is low, gap graded aggregates can produce good concrete.

- Open graded: It refers to a type of gradation where the particles that are represented by the finer range is of a very small percentage. Therefore there is a shortage of finer particles that can fill the voids between the coarser particles. This would cause a lot of air voids. The gradation curve is nearly flat and is near zero in the finer size range and is vertical in the intermediate size range (Pavement Interactive, 2011).
- Uniformly graded: If most of the particles in a gradation are represented by a very narrow size range it is known as a uniformly graded curve. It is mainly due to the fact that most of the particles have similar sizes. The curve that demonstrates such a gradation is steep since it is only within a narrow size range (Pavement Interactive, 2011). Uniformly graded aggregates cannot be well packed hence the concrete produced will contain more pores. Therefore to mitigate this issue a lot of paste needs to be added to the mix.

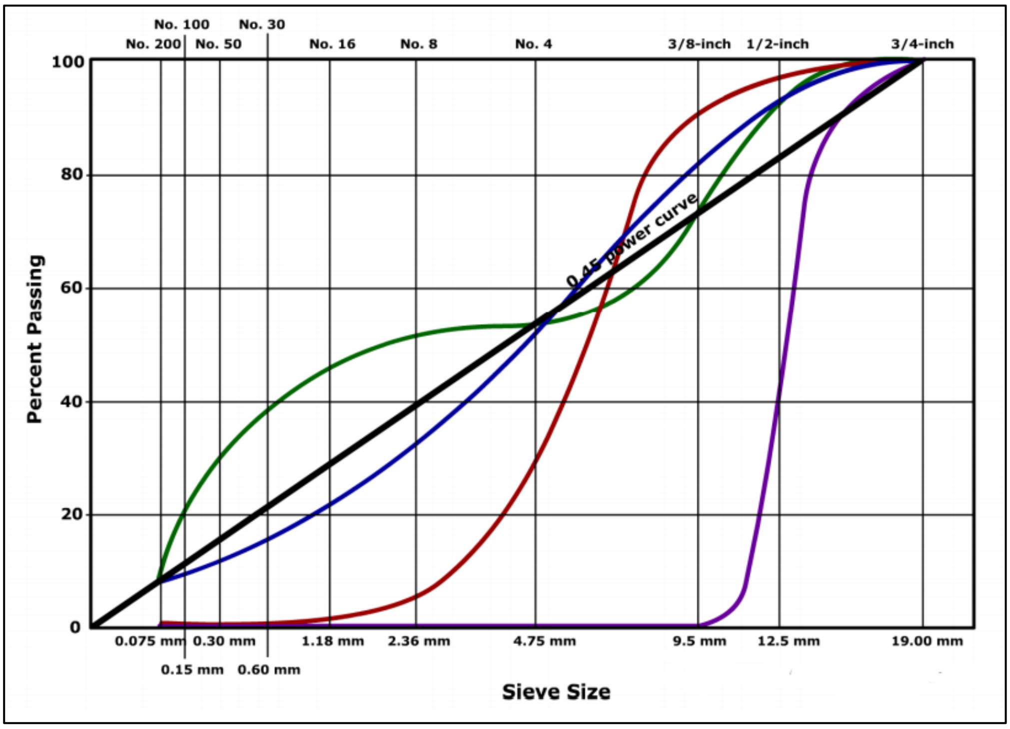


Figure 4. 2: Type of Aggregate Gradation

Source: (Pavement Interactive, 2011)

🟦 - Dense gradation
🟩 - Gap gradation
🟥 - Open gradation
🟪 - Uniform gradation

When analyzing the particle size distribution curves given in Figure 4.1, of NCA and RCA we can see that there isn’t a significant difference between them. Furthermore according to Figure 4.1, the particle size distribution curves of NCA and RCA both demonstrate a uniform gradation. It can be clearly seen that most of the particles are represented in a very small size range. Furthermore the particle size distribution curves of NCA and RCA are steep.

According to Table 4.1, there is a very small difference between the average particle size (D50) of RCA and NCA, it is around 0.41 mm. The effective particle size (D10) is the particle size of an aggregate sample where 10% of particles are finer and 90% of particles are coarser than that particular size. According to Table 4.1, there is a very small difference between the effective particle size (D10) of RCA and NCA, it is around 0.28 mm. The particle size represented by D30 and D60 of an aggregate sample denotes that 30% or 60% of particles are respectively finer and 70% or 40% of particles are respectively coarser than that particular size. According to Table 4.1, there is a very small difference between the D30 and D60 particle sizes of RCA and NCA; it is around 0.29 mm and 0.47 mm respectively. According to Table 4.1, it can be stated that the coefficient of curvature (Gradation) (Cc) is between 1-3 for both NCA as well as RCA. Hence it can be said that it is a well graded aggregate sample. But when analyzing Table 4.1, it can be seen that the coefficient of uniformity (Cu) is less than 4 for both NCA as well as RCA. This indicates that both aggregate samples are poorly graded or uniformly graded.

4.1.1.2. Specific Gravity and Water Absorption Test Results

In general the specific gravity of an aggregate sample is the ratio between the mass of an aggregate sample to the mass of water that has an equal absolute volume as that of the aggregate sample. The pores present in aggregates can be either permeable or impermeable depending on how they are situated in the aggregate sample (Neville, 2011). The specific gravity of an aggregate is generally used in calculations carried out in attaining the appropriate mix design and control factors, such as when computing the compaction factor needed for the workability measurements or when computing the volume of aggregate according to the mix design ((Shetty, 2013), (Kosmatka et al, 2002)). Even though the specific gravity of aggregates is used to calculate quantities it is not a suitable parameter that can be used to measure its quality. If a material having a fixed characteristic petrology indicates any variation in its specific gravity value this would directly reflect upon the materials porosity hence in such a scenario the specific gravity needs to be specified (Neville, 2011). The specific gravity of natural aggregates mostly falls in the range between 2.4 and 2.9 (Kosmatka, Kerkhoff & Panarese, 2002). In the case of artificial aggregates the specific gravity values will be either very much lower or very much higher than this range. When analyzing the data given in Table 4.2 it can be said that the specific gravity values of both NCA and RCA are within the range of natural aggregates (i.e. 2.4-2.9). According to Table 4.2 the specific gravity value of RCA is lesser than that of NCA. That is when we take an equal volume of NCA and RCA; NCA will be much heavier than RCA. It is mainly due to the light weight porous attached mortar on the surface of the RCA.

Table 4. 2: Results of the Specific Gravity and Water Absorption Test of Recycled Coarse Aggregates (RCA) and Natural Coarse Aggregates (NCA)

	Natural Coarse Aggregates (NCA)	**Recycled Coarse Aggregates (RCA)**
Avg. Water Absorption (As A % of Dry Mass) (Mean ± SE)	0.39 ± 0.01	6.01 ± 0.06
Relative Density on SSD Basis (Mean ± SE)	2.77 ± 0.01	2.42 ± 0.00
Apparent Relative Density (Mean ± SE)	2.79 ± 0.01	2.64 ± 0.00
Relative Density on an Oven Dried Basis (Mean ± SE)	2.76 ± 0.01	2.28 ± 0.00

Therefore, when considering about aggregates there are several types of specific gravity values that need to be defined. In the current study the specific gravity on saturated and surface dry (SSD) basis, apparent specific gravity and the specific gravity on an oven dried basis were considered.

The specific gravity on saturated and surface dry (SSD) basis of an aggregate is obtained when the volumes of the impermeable pores present in the aggregate and the permeable pores present in the aggregate is included in to the total volume of the solid. The ratio between the saturated and surface dry (SSD) mass of an aggregate sample to the mass of water that has an equal absolute volume as that of the aggregate sample, the impermeable and permeable pores present in the aggregate, is denoted as the specific gravity on saturated and surface dry (SSD) basis of an aggregate sample (Neville, 2011). In order to determine the amount of aggregate needed to produce a given volume of concrete and to determine the yield of concrete, the specific gravity of an aggregate in its saturated and surface dry (SSD) condition is usually considered in the calculations carried out prior to the production of concrete. It is mainly due to the fact that the water held up in the pores of an aggregate does not chemically react with cement hence it too can be counted in as part of the aggregate.

The apparent specific gravity of an aggregate is obtained when the volume of the impermeable pores present in the aggregate is included in to the total volume of the solid and the permeable pores present in the aggregate is excluded from it. The ratio between the oven dried mass of an aggregate sample to the mass of water that has an equal absolute volume as that of the aggregate sample and the impermeable pores present in it, is denoted as the apparent specific gravity of the aggregate sample (Neville, 2011). The apparent specific gravity of an aggregate depends on the amount of voids present in the aggregate and the relative density of the constituent minerals of the aggregate.

When analyzing the data given in Table 4.2 it can be pointed out that there is only a small variation between the values given by the different types of specific gravity of NCA but in the contrary it is quite different when observing the specific gravity values of RCA. Generally NCA has fewer pores that are permeable or impermeable this explains the minute variation in the specific gravity; on the other hand RCA has a large amount of permeable pores due to the attached old cement mortar present on its surface. It can be observed that there is a large difference between the apparent specific gravity and the specific gravity on an oven dried basis of RCA with comparison to NCA. When computing the apparent specific gravity the volume represented by the impermeable pores are considered while the permeable pores or capillary pores are not taken in to consideration but when computing the specific gravity on an oven dried basis the volume represented by both the permeable and impermeable pores are taken in to consideration. Therefore the specific gravity on an oven dried basis of RCA is 0.36 units lesser than that of the apparent specific gravity of RCA. This difference is 12 times greater than that obtained from the NCA sample which was only 0.03 units. According to Table 4.2 it can be seen that the specific gravity of NCA at a SSD condition (i.e. 2.77 ± 0.01) is 0.35 units greater than that of RCA (i.e. 2.42 ± 0.00). This indicates that the volume of permeable and impermeable pores present in the RCA sample is much higher than that present in NCA.

The characteristics of the internal pores present in the aggregates are of vital importance when it comes to the study of its properties. The porosity of an aggregate sample, its permeability and its absorption capacity all are interlinked together and has a significant effect on the properties of the concrete produced by the aggregates. Such as resistance to freezing and thawing, its resistance to abrasion, its chemical stability and the bond between the hydrated cement paste and the aggregate.

The pore sizes of an aggregate vary within a wide spectrum. It was stated by Neville (2011) that the pore sizes found in aggregates can sometimes be large enough to be viewed through a microscope or even through the naked eye. It was further stated that the finest pores in the aggregate are still larger than the gel pores present in the cement paste. The voids present in an aggregate are generally within the solid itself and in some instances will be present on the surface of the aggregate. The mortar or the cement paste finds it difficult or in some instances cannot penetrate in to the fine pores present on the surface of the aggregate. Hence these fine pores are also considered as part of the solid composition when computing the aggregate quantity needed for the concrete production. It should be noted that water can easily penetrate in to these pores. The rate and the quantity of penetration depend mainly upon the continuity, size fraction and the total volume of the pores. When considering RCA with NCA it can be clearly seen that RCA has a lot of voids present on its surface due to the adhered mortar and micro cracks caused by the crushing process. These pores are large enough to be seen by the naked eye. Therefore RCA has a high susceptibility of absorbing free water than NCA due to the large amount of pores present on its surface. Hence it explains why the water absorption of RCA shows a value that is approximately 15.41 times than that of NCA. The porosity of an aggregate sample will directly affect the overall porosity of concrete, since almost ¾ of the total volume of the concrete is comprised with it. Hence it is evident that the high water demand of RCA is a major drawback when considering it as a suitable replacement for NCA. Therefore in the current study the main objective was to block and reduce the size of these pores present on the surface of the RCA by coating it with a slurry that contains water, RHA and lime or cement.

The moisture conditions of aggregates are given in Figure 4.3. If there is water present on the surface of the aggregate it is said to be in its damp or moist condition. The aggregate under consideration is said to be in its saturated and surface dry condition when all the interconnected voids in the aggregate are filled with water. The aggregate under consideration is said to be in its air dry condition when some of the interconnected voids in the aggregate are filled with water. Generally the aggregate sample obtained from a stock pile will be in its air dry condition. When all the moisture present in the aggregate sample is removed, it is said to be in its oven dry condition or bone dry condition.

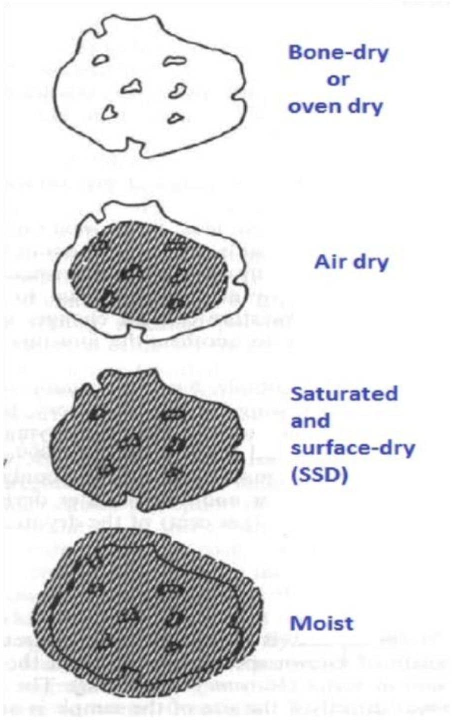


Figure 4. 3: Moisture Condition in Aggregate

Source: (Foundation, Concrete and Earthquake Engineering, 2014)

It was stated by Neville (2011) that gravel generally shows a higher water absorption capacity than crushed rock having the same petrological characteristics. It is mainly due to the formation of pores on the surface of the rock due to weathering actions. It cannot be clearly stated that the water absorption of the aggregate has an influence on the concrete strength. But the voids present on the surface of the aggregate have an immense effect on the bond strength between the cement paste and the aggregate and therefore will cause an impact on the strength of the concrete. It is assumed by many that at the setting time of concrete the aggregates used are in a saturated and surface dry condition (Neville, 2011). When dry aggregates are used an adequate amount of water is absorbed by it from the concrete mix in order to saturate the aggregate. But these aggregate particles can also rapidly be coated by the cement paste. This will preclude the need of the aggregate particles from been saturated hence reducing the water loss observed in the mix when dry aggregates are used. This can particularly be seen in coarse aggregates where the penetration of water can reach further into the surface of the aggregate. When the aggregate does not absorb water in the mix to get fully saturated this will cause less effect on the effective water-cement ratio. This phenomenon can be observed when a rich mix is used since the rapid coating of aggregate with cement can occur but when a wet or lean mix is used the aggregates will achieve their saturated and surface dry condition at the setting time of the concrete. The order been used to feed the constituents in to the mixer can also have an impact on the concrete mix.

The workability of a fresh concrete mix will also be affected by the water absorption capacity of the aggregates been used in the mix. Neville (2011) states that the loss observed in the workability due to water been absorbed by aggregates becomes smaller beyond 15 minutes of mixing time. It is mainly due to the fact that the water absorption of aggregates reduces or is halted due to the coating of the aggregate particles with the mortar or cement paste. Hence according to Neville (2011) it is said to be suitable to analyze the water absorption of aggregates for 10 to 30 minutes since in practice the aggregate will never achieve its saturated and surface dry condition.

4.1.1.3. Bulk Density Test Results

When considering the imperial or American systems the absolute density is referred to as that when specific gravity is multiplied by the density of water. The weight or mass of an aggregate sample needed to fill a container having a set unit volume is denoted as the bulk density or the unite weight of the particular aggregate sample. Here the volume is a collaboration of the volume of aggregates itself and the volume of the pores in-between the aggregate particles (Kosmatka et al, 2002). When volume batching is carried out to produce concrete it is essential that the bulk density of the aggregate samples are known. The bulk density is generally used to convert the values represented by mass to values represented by volume. When a coarse aggregate sample having a fixed specific gravity has a high bulk density it indicates that there are few voids in between the coarse aggregate particles that need to be filled with mortar. According to Neville (2011) the bulk density test has been used to proportion mixes for concrete production. When using light weight and heavy weight aggregates their bulk density is of utmost importance for the production of concrete.

The bulk density of an aggregate sample mainly depends on how densely the aggregate particles are packed in the container used to obtain its value. The degree of packing of an aggregate sample for a given specific gravity depends on in its particle size distribution and its particle shape. An aggregate sample that is made up with particles that have the same size will have a limited compaction but an aggregate sample that is made up with particles that have different sizes will have a very good compaction since the smaller particles can fill the voids in-between the larger particles hence increasing its bulk density. The angularity of the aggregate particles will also increase the voids in-between the aggregate particle. The closeness of packing of an aggregate sample mainly depends upon its particle shape. Furthermore the degree of compaction depends on the actual compaction achieved by the aggregate sample. When the centers of the spherical particles having equal sizes lie at the apexes of imaginary tetrahedral the densest pacing is obtained when their centers are directed to the corners of imaginary cubes a loose packing is achieved. The degree of packing of an aggregate sample will reduce due to the bulking effect caused by the surface water present on it. It is very difficult to achieve the degree of compaction that was obtained in the laboratory on site. The bulk density obtained through lab base experiments cannot be directly used on site in order to convert proportions given by mass in a mix design to proportions of volume in order to carry out the volume batching method to produce concrete (Neville, 2011).

The aggregates that are usually used to make normal weight concrete usually have an approximate bulk density that ranges between 1200 kg/m3 and 1750 kg/m3 (Kosmatka et al, 2002). According to Table 4.3 it can be seen that the bulk density achieved by both degrees of compaction of NCA and RCA all fall within this range. Furthermore according to Table 4.3 the compacted bulk density of NCA is approximately 1.22 times greater than that of RCA. It is mainly due to the light weight porous attached mortar on the surface of the RCA. Therefore when a similar volume of RCA and NCA is weighed the weight of RCA will be lesser than that of NCA. Another factor that could have caused the bulk density of RCA to be lesser than that of NCA is due to the angular and rough surface texture of RCA. The angular particles of RCA will cause more voids between the large particles and the rough surface texture will produce a friction against a dense compaction than in the case of NCA hence increasing the total volume of RCA thereby reducing its bulk density. According to Neville (2011) the ratio between the loose bulk density and the compacted bulk density in normal circumstances lie between 0.87 and 0.96. When analyzing the Table 4.3 it can be seen that the ratio between the loose bulk density and the compacted bulk density of NCA lie in between the specified region but when considering RCA it is around 0.03 greater than the usual range.

Table 4. 3: Bulk Density Test Results

	Bulk Density (Kg/M^3) (Mean ±SE)		$\frac{\textit{Loose bulk density}}{\textit{Compacted bulk density}}$
	Compacted	**Loose**	
Natural Coarse Aggregates (NCA)	1598.85 ± 8.85	1498.12 ± 2.00	0.94
Recycled Coarse Aggregates (RCA)	1314.06 ± 5.18	1299.33 ± 1.53	0.99

4.1.1.4. Los Angeles Abrasion Value (LAAV) Test Results

The resistance a concrete aggregate has against the failure due to wear is known as its hardness (Neville, 2011). The resistance against wear of an aggregate sample is of utmost importance when it is used to produce concrete to construct floor surfaces that are prone to heavy traffic, ware house floors and pavement construction that undergo continuous abrasion (Neville, 2011). When considering a road surface, abrasion is caused on the road aggregates due to the friction caused between the soil particles that are present in the pneumatic tires of vehicles and the surface of the road (Shetty, 2013). Furthermore wheels that contain a steel ream impose a large abrasion on the road and pavement surfaces.

Three tests have been recognized to identify the resistance that the aggregate sample has against wear by attrition of aggregate particles with one another or by rubbing the surface of the aggregate sample been tested by a foreign material. They are the attrition (Deval) test, the Dorry abrasion test and the Los Angeles Abrasion test ((Shetty, 2013), (Neville, 2011)). When it comes to denote the resistance against wear of an aggregate sample that is of interest the Los Angeles Abrasion test is most often used in construction work. This test is a combination of the attrition and the abrasion actions. In the Los Angeles abrasion test the aggregate sample is susceptible to wear due to the abrasion and attrition actions caused on them due to mixing of these aggregate samples with standard iron balls in a drum that is rotated for a specific number of revolutions (Neville, 2011). The percentage of the aggregate sample that were broken down in to particles finer than the opening size of the 1.70 mm sieve is denoted as the Los Angeles abrasion value (LAAV). It is stated by Neville (2011) that the Los Angeles abrasion value indicates a very good correlation with the actual wear of the concrete aggregate when it is used to produce concrete and with the compressive strength and the flexural strength of the concrete made with the specific concrete aggregate.

According to Table 4.4, it can be clearly seen that the LAAV of RCA is approximately 1.64 times greater than that of NCA. Therefore it can be concluded that RCA has a weaker resistance to wear than NCA. It is mainly due to the removal of the attached old cement mortar present on the surface of the RCA due to the abrasion and attrition actions. The removed attached mortar then gets added up in to the fines, thereby increasing its LAAV. According to the IRC specifications the LAAV of an aggregate sample to be suitable to be used in a specific road construction is given in Table 4.5. According to Table 4.4, the LAAV of NCA is around 28.07%, it is lesser than 30%, and hence it can be pointed out that according to the IRC specifications that NCA is suitable to be used in any type of pavement described in Table 4.5. According to Table 4.4, the LAAV of RCA is around 46%, it is in-between 40% and 60%, and hence it can be pointed out that according to the IRC specifications the suitability of RCA is limited to the use in bituminous bound macadam, WBM base course with bituminous surfacing and water bound macadam sub base course.

Table 4. 4: Los Angeles Abrasion Value (LAAV) Test Results

	Los Angeles Abrasion Value (LAAV) (%) (Mean ±SE)
Natural Coarse Aggregate (NCA)	28.07 ± 1.43
Recycled Coarse Aggregate (RCA)	46 ± 2.70

Table 4. 5: IRC (Indian Road Congress) Specification for LAAV Test

Sl. No.	Type of Pavement	Max. Permissible Abrasion Value In %
1	Water Bound Macadam Sub Base Course	60
2	WBM Base Course With Bituminous Surfacing	50
3	Bituminous Bound Macadam	50
4	WBM Surfacing Course	40
5	Bituminous Penetration Macadam	40
6	Bituminous Surface Dressing, Cement Concrete Surface Course	35
7	Bituminous Concrete Surface Course	30

Source: (The Constructor - Civil Engineering Home, 2011)

4.1.1.5. Aggregate Impact Value (AIV) Test Results

The resistance a concrete aggregate has against the failure due to impact is known as its toughness. In the aggregate impact value test the resistance of an aggregate towards an abrupt impact or shock is measured. That is when the AIV value of an aggregate sample is high it denotes that it has a low resistance to impact and is a weak aggregate sample. According to Neville (2011) if the aggregate sample is to be used in heavy duty floors the AIV value should not exceed 25%, if the aggregate sample is to be used in concrete for wearing surfaces such as runways, roads and pavements the AIV vale should not exceed 30% and if the aggregate sample is to be used in other concrete the AIV vale should not exceed 45%. When considering the AIV test results shown in Table 4.6, it can be clearly seen that the AIV value of RCA is approximately 2.4 times greater than that of NCA. This is mainly due to the removal of the attached mortar on the surface of the RCA by the impact caused by the hammer. Hence the attached mortar gets collected in to the fines increasing the

AIV value of the RCA sample. Furthermore when considering the AIV value of NCA it can be seen that it can be used in heavy duty floors since its AIV value is less than 25%, but when considering the AIV value of RCA it can be seen that it can be used in concrete for wearing surfaces since its AIV value is in-between 25% and 30%. It should also be noted that there is no direct correlation between the crushing value of an aggregate sample and the strength of the concrete made using it or the performance of it in the concrete (Neville, 2011).

Table 4. 6: Aggregate Impact Value (AIV) Test Results

	Aggregate Impact Value (AIV) (%)(Mean ±SE)
Natural Coarse Aggregate (NCA)	11.41 ± 0.04
Recycled Coarse Aggregate (RCA)	27.34± 0.24

4.1.2. Rice Husk Ash (RHA)

4.1.2.1. Chemical Testing

4.1.2.1.1. Loss on Ignition Test Results

Loss on Ignition (LOI) represents the amount of carbon present in the RHA sample. When rice husk is burnt in a temperature lesser than the required temperature for it to be completely burnt, a significant amount of unburned carbon will be present in the RHA left behind. It is said that the carbon present in RHA has a substantial impact on its initial and final setting time (Robert, 1990). But the carbon present in RHA has no significant influence on its strength gain (Robert, 1990). According to Nagrale et al., the carbon content of RHA should not exceed 10% in order for it to have a high performance. When observing Table 4.7 it can be seen that the LOI of the RHA samples that fall within this specific limit are A1, A2 and P3.

Table 4. 7: Loss on Ignition Test Results

Type of RHA		**Loss On Ignition (%) (Mean ± SE)**
RHA Samples Obtained From Ampara	A1	3.79 ± 0.20
	A2	9.14 ± 0.34
RHA Samples Obtained From Polonnaruwa	P1	31.0 ± 0.26
	P2	14.48 ± 0.19
	P3	2.94 ± 0.03
	P4	21.96 ± 0.21

4.1.2.1.2. Measurement of SiO_2, Al and Ca Content of RHA

When considering RHA the major compound that plays an influential part in the pozzolanic reaction is the percentage of SiO2 present in it. According to Robert et al., the engineering performance of any pozzolan cannot be depicted by the analysis of oxides present in them, except when the difference between the percentage of SiO2 and lime present in the pozzolan is around 34 %. This indicates that there is no vitreous phase in the material and hence is an indirect indication that the respective pozzolan has the potential to be highly reactive. It can be stated that if the pozzolan exhibits high chemical reactivity it will have a higher strength gain (Robert, 1990). This does not mean that the durability of the resultant product can be guaranteed. According to Table 4.8, and Table 4.9, it can be seen that the difference between the percentage of SiO2 and lime present in the RHA samples tested are greater than 34 %, hence according to Robert et al., the engineering performance of the RHA samples used in the testing cannot be depicted by the analysis of oxides present in it.

Our main objective was to select the RHA sample that had the highest amount of SiO2 present in it so that, the pozzolanic reaction would occur with Ca(OH)2 and it would have a higher reactivity with Ca(OH)2. Therefore the ‘A1’ RHA sample was selected to treat RCA since it had the highest percentage of SiO2 present in it (=75.02 ± 0.52%).

Table 4. 8: SiO_2 Content of the RHA Samples

Type of RHA		**Sio_2 Content (%) (Mean ± SE)**
RHA Samples Obtained From Ampara	A1	75.02 ± 0.52
	A2	64.41 ± 0.43
RHA Samples Obtained From Polonnaruwa	P1	53.86 ± 0.70
	P2	65.74 ± 0.09
	P3	71.21 ± 0.16
	P4	58.51 ± 0.04

Table 4. 9: Al and Ca Content of RHA (Atomic absorption spectrometer method)

Type of RHA		**Al (%) (Mean ± SE)**	**Ca(%) (Mean ± SE)**
RHA Samples Obtained From Ampara	A1	0.61 ± 0.01	0.08 ± 0.00
	A2	7.01 ± 0.00	20.62 ± 0.00
RHA Samples Obtained From Polonnaruwa	P1	2.87 ± 0.01	0.90 ± 0.00
	P2	0.35 ± 0.00	0.18 ± 0.00
	P3	0.32 ± 0.00	0.25 ± 0.00
	P4	0.26 ± 0.00	0.20 ± 0.00

4.1.2.2. Determination of Physical Properties of RHA

4.1.2.2.1. Test Results of Particle Density of RHA

Table 4. 10: Particle Density of the RHA Samples

Type of RHA		Specific Gravity (Mean ±SE)
RHA Samples Obtained From Ampara	A1	2.14 ± 0.00
	A2	1.99 ± 0.01
RHA Samples Obtained From Polonnaruwa	P1	1.85 ± 0.10
	P2	1.95 ± 0.02
	P3	2.16 ± 0.03
	P4	2.11 ± 0.02

4.1.2.2.2. Particle Size Distribution of RHA

It is usually very essential to grind the pozzolanic material in order to gain substantial reactivity and to guarantee that the pozzolanic reaction is significant at an early age. According to Hanna & Afify (1976), the particles that had a size fraction lesser than 3 μm had a paramount effect on the strength gain at 1 day whereas the particles that had a size fraction between 3-25 μm had a greater effect on the strength gain at 28 days. When ash is to be ground to a finer size fraction the standards need to fulfilled and the cost-benefits of the grinding process need to be taken in to consideration. When the particles do not have a significant inherent porosity, the surface area and the particle size of some pozzolanas is said to be allied (Robert, 1990). When considering the particles of RHA there exists an internal pore structure, hence it shows a greater surface area than that been predicted in the particle size distribution.

According to Robert et al., when the pozzolan is to be used with cement it is normally inter-ground with cement than blended. When inter-grinding the pozzolan with cement the end product will exhibit a wide range of particle sizes (Robert, 1990). Therefore Davis (1950), states that it is best to add the pozzolan at the mixer itself since it gives better control.

In order for many pozzolans to have a satisfactory reactivity they need to be ground to at least a Blaine of 5000 cm^2/g (Campbell, Weise & Love, 1982). Finer the pozzolan the stronger the resulting material would be.

Many pilot tests need to be carried out in order to decide on how much grinding of RHA is needed, the correct capacity needed to be used and the type of grinding mill needed so that the end product will have a high pozzolanic reactivity.

In the current study the RHA samples were ground by using a LAAV machine for a time duration of 1 ½ hours (i.e. 1500 revolutions) having a speed of 30 revolutions per minute. When observing the particle size distribution of the RHA samples before grinding them and after grinding them as shown in Figure 4.4, Figure 4.5, Figure 4.6, Figure 4.7, Figure 4.8 and Figure 4.9, it can be seen that there is a reduction in the particle size distribution due to grinding. It can be further seen that the D50 values of the RHA samples after grinding them for time duration of 1 ½ hours in the LAAV machine is greater than 130-180 μm. In order for the RHA sample to exhibit high pozzolanicity at least 60 % of passing should be lesser than the mean particle size of cement which is around 10-30 μm (Rukzon, Chindaprasirt & Mahachai, 2009). It is evident that the grinding method used in the current study is not sufficient to grind the RHA particles in order for it to be finer than the mean particle size of ordinary Portland cement. It should be highlighted that even though the RHA particles were not ground to a very fine powder, it still when mixed with cement could approximately reduce 1.5-2.5 % of the water absorption of RCA. But if the mean particle size of RHA was reduced to be finer than cement the reduction in the water absorption of RCA could have been further reduced.

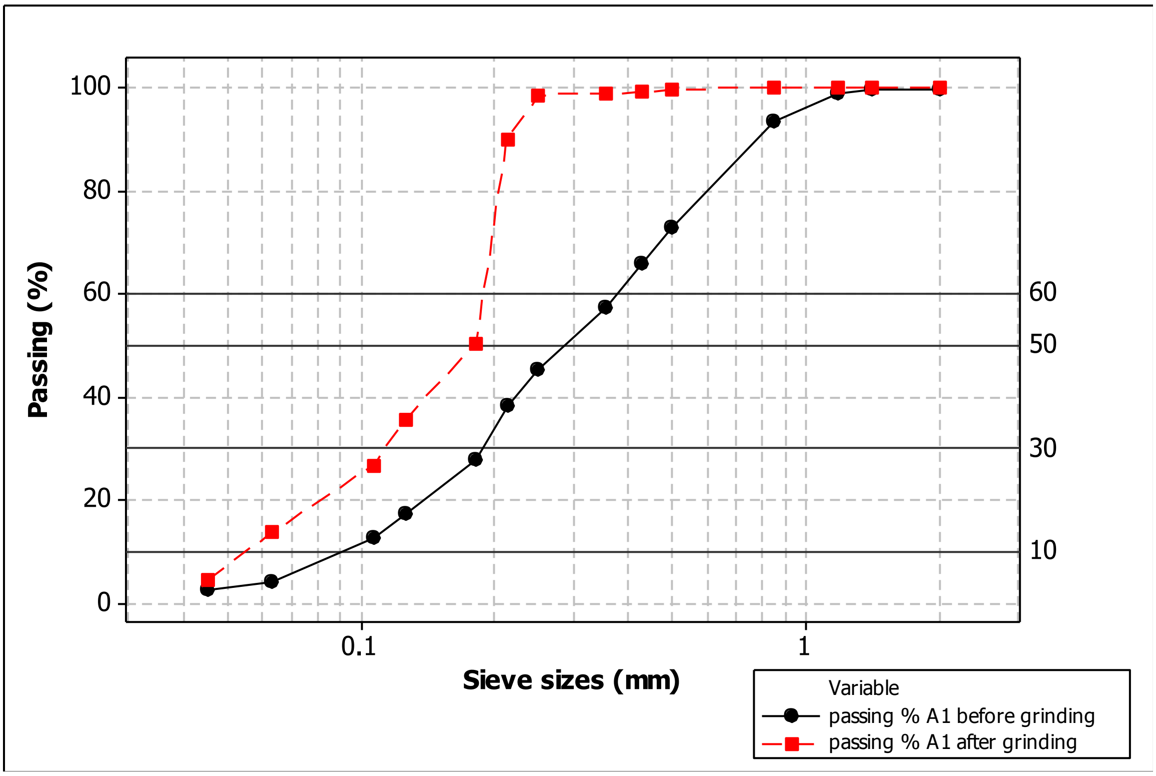


Figure 4. 4: Particle Size Distribution of Unground RHA and Ground RHA from Ampara (A1)

Table 4. 11: D10, D30, D50 and D60 Values Derived From the Particle Size Distribution Curves of Unground RHA and Ground RHA from Ampara (A1)

		Unground RHA (A1)	**Ground RHA (A1)**
Effective Sizes	D10 (Mm)	0.0929	0.0560
	D30 (Mm)	0.1873	0.1132
	D50 (Mm)	0.2930	0.1795
	D60 (Mm)	0.3784	0.1879
Coefficient of Curvature (Gradation) (Cc)		0.9986	1.2190
Coefficient of Uniformity (Cu)		4.0747	3.3580

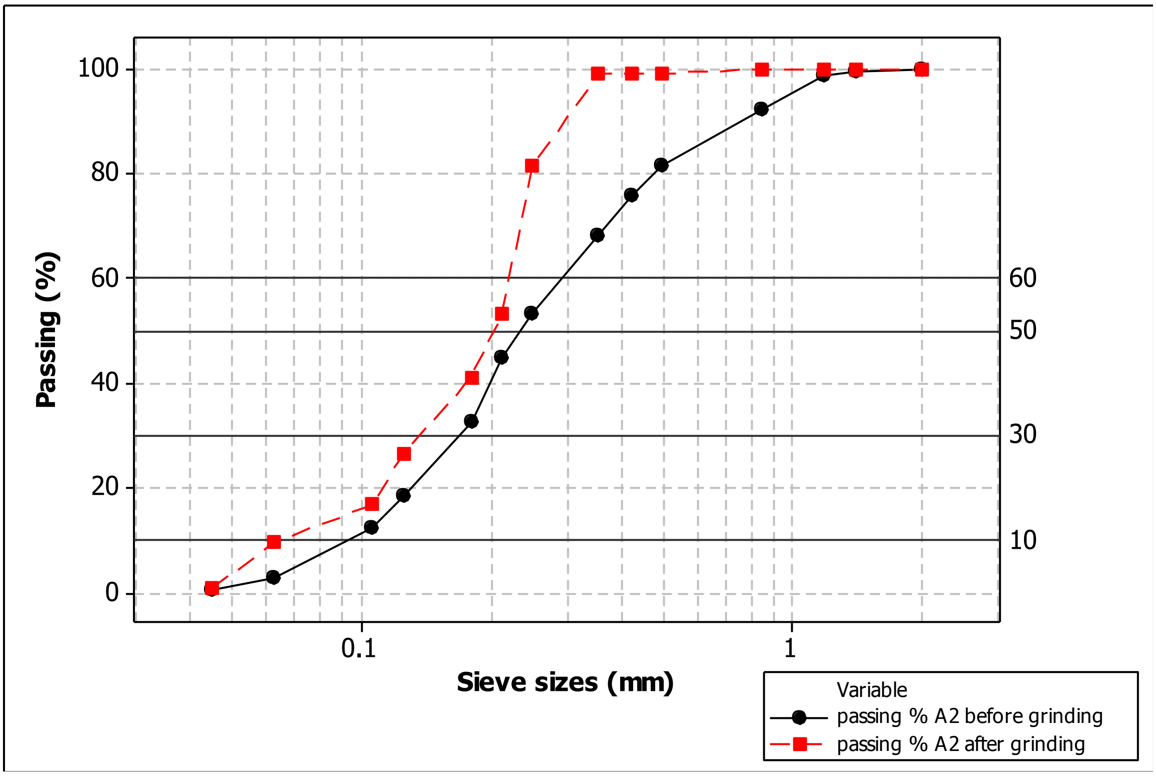


Figure 4. 5: Particle Size Distribution of Unground RHA and ground RHA from Ampara (A2)

Table 4. 12: D10, D30, D50 and D60 Values Derived From the Particle Size Distribution Curves of Unground RHA and Ground RHA from Ampara (A2)

		Unground RHA (A2)	**Ground RHA (A2)**
Effective Sizes	D10 (Mm)	0.0949	0.0655
	D30 (Mm)	0.1701	0.1381
	D50 (Mm)	0.2352	0.2038
	D60 (Mm)	0.2966	0.2212
Coefficient of Curvature (Gradation) (Cc)		1.0281	1.3160
Coefficient of Uniformity (Cu)		3.1257	3.3789

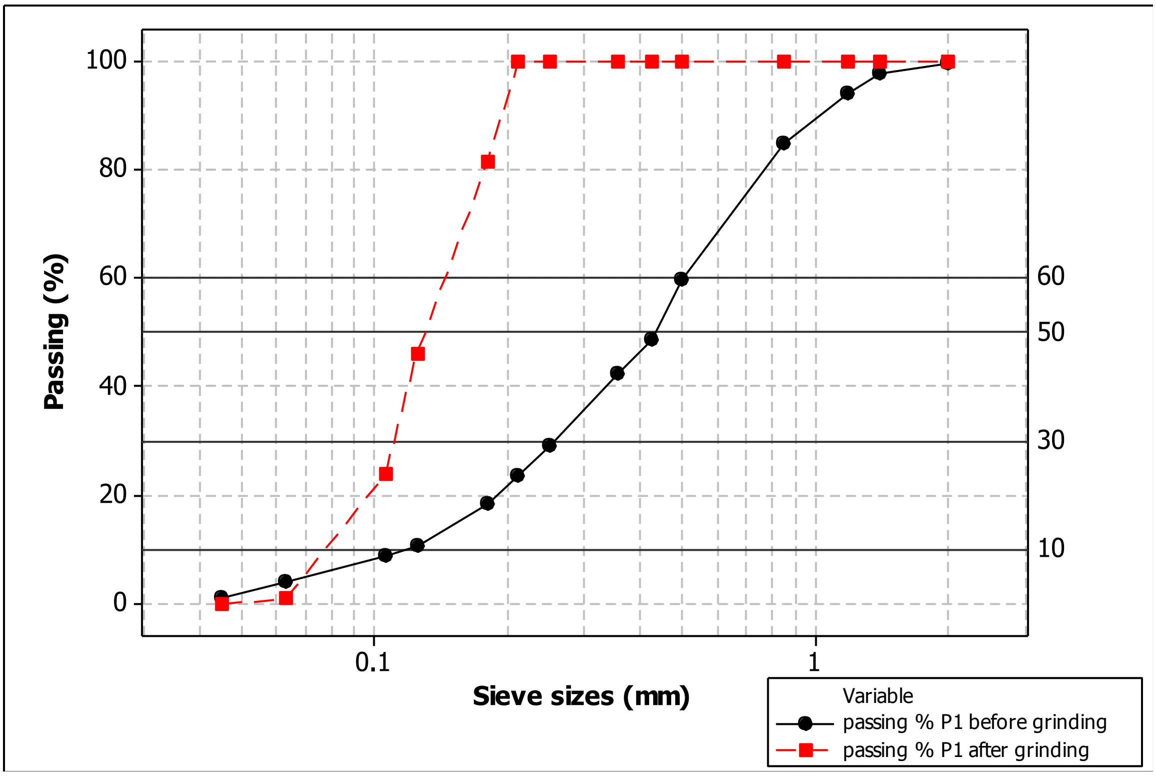


Figure 4. 6 : Particle Size Distribution of Unground RHA and Ground RHA from Polonnaruwa (P1)

Table 4. 13: D10, D30, D50 and D60 Values Derived From the Particle Size Distribution Curves of Unground RHA and Ground RHA from Polonnaruwa (P1)

		Unground RHA (P1)	**Ground RHA (P1)**
Effective Sizes	D10 (Mm)	0.1181	0.0799
	D30 (Mm)	0.2573	0.1111
	D50 (Mm)	0.4345	0.1308
	D60 (Mm)	0.5047	0.1464
Coefficient of Curvature (Gradation) (Cc)		1.1104	1.0550
Coefficient of Uniformity (Cu)		4.2740	1.8336

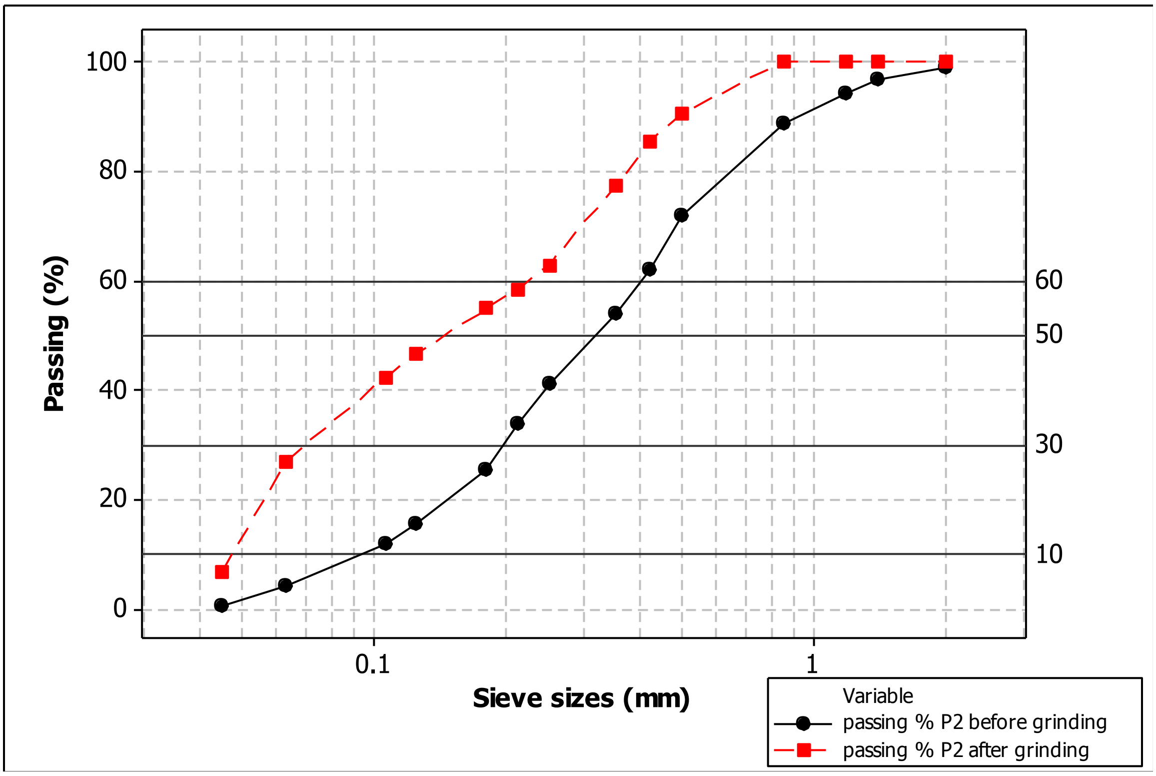


Figure 4. 7: Particle Size Distribution of Unground RHA and Ground RHA from Polonnaruwa (P2)

Table 4. 14: D10, D30, D50 and D60 Values Derived From the Particle Size Distribution Curves of Unground RHA and Ground RHA from Polonnaruwa (P2)

		Unground RHA (P2)	**Ground RHA (P2)**
Effective Sizes	D10 (Mm)	0.0948	0.0478
	D30 (Mm)	0.1973	0.0714
	D50 (Mm)	0.3232	0.1468
	D60 (Mm)	0.4066	0.2246
Coefficient of Curvature (Gradation) (Cc)		1.0099	0.4754
Coefficient of Uniformity (Cu)		4.2883	4.6987

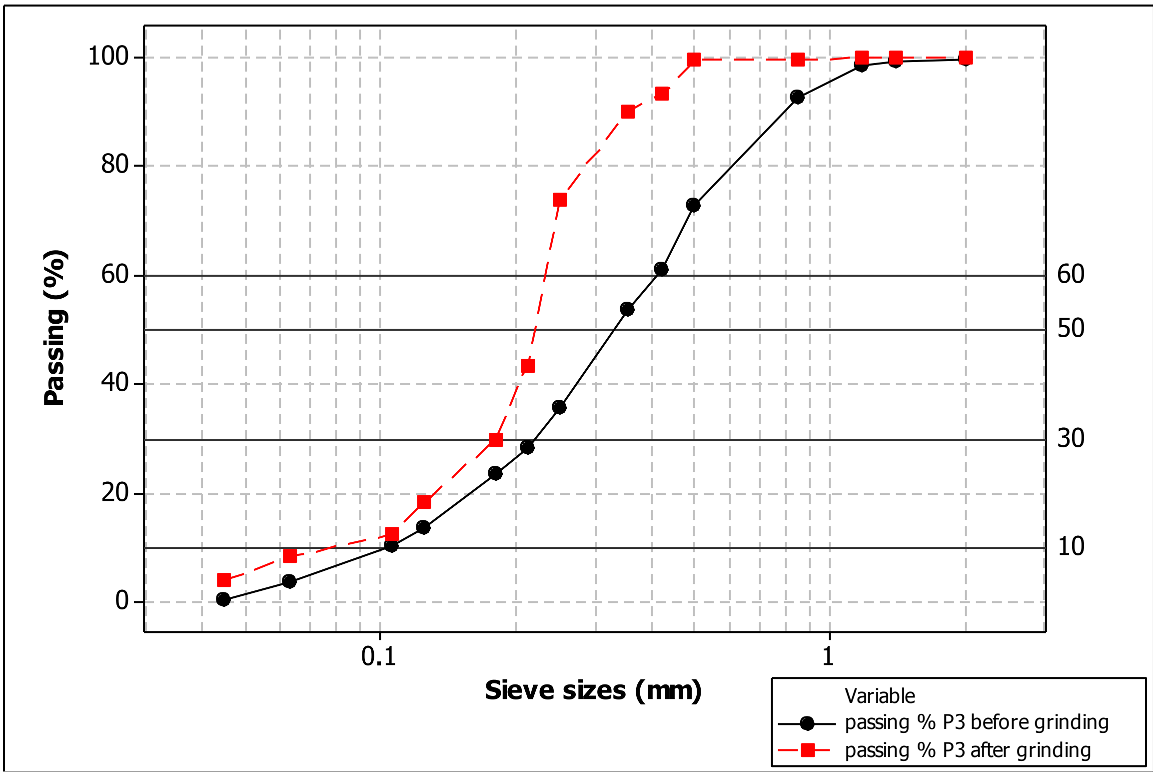


Figure 4. 8: Particle Size Distribution of Unground RHA and Ground RHA from Polonnaruwa (P3)

Table 4. 15: D10, D30, D50 and D60 Values Derived From the Particle Size Distribution Curves of Unground RHA and Ground RHA from Polonnaruwa (P3)

		Unground RHA (P3)	**Ground RHA (P3)**
Effective sizes	D10 (mm)	0.1028	0.0785
	D30 (mm)	0.2197	0.1797
	D50 (mm)	0.3332	0.2200
	D60 (mm)	0.4131	0.2326
Coefficient of curvature (Gradation) (Cc)		1.1372	1.7684
Coefficient of uniformity (Cu)		4.0203	2.9634

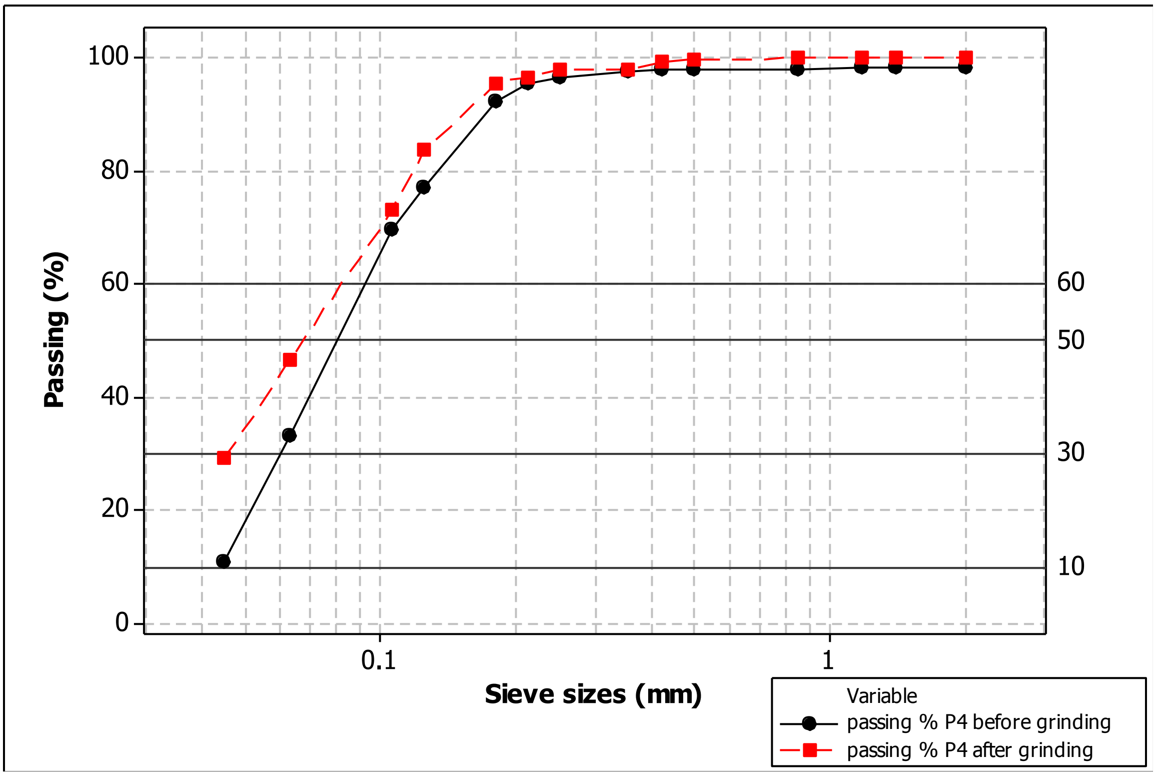


Figure 4. 9: Particle Size Distribution of Unground RHA and Ground RHA from Polonnaruwa (P4)

Table 4. 16: D10, D30, D50 and D60 Values Derived From the Particle Size Distribution Curves of Unground RHA and Ground RHA from Polonnaruwa (P4)

		Unground RHA (P4)	**Ground RHA (P4)**
Effective Sizes	D10 (Mm)	0.0442	0.0253
	D30 (Mm)	0.0604	0.0458
	D50 (Mm)	0.0827	0.0683
	D60 (Mm)	0.0945	0.0846
Coefficient of Curvature (Gradation) (Cc)		0.8723	0.9808
Coefficient of Uniformity (Cu)		2.1401	3.3490

4.1.2.3. Selecting the Best RHA Sample

The 'A1' RHA sample obtained from a rice mill situated in Ampara was selected to treat RCA since it had the highest percentage of SiO_2 present in it (=75.02 ± 0.52%) and the percentage of carbon present in the RHA samples was below 10%.

4.2. Properties of RCA after Surface Treatment

4.2.1. Treatment of RCA with Ground Rice Husk Ash (RHA) - Lime Slurry

4.2.1.1. Specific Gravity and Water Absorption of the Coated RCA

4.2.1.1.1. Water Absorption

The graphs shown by Figure 4.10 and 4.11 both represent the same water absorption values of treated RCA treated with varying RHA: Lime ratios for different slurry (Liquid: Solid) ratios. The only difference between the graphs is the categorical variables that had been selected to construct them. In Figure 4.10 the categorical variable was given as the RHA percentage (i.e. RHA%: lime %) and in Figure 4.11 the categorical variable was given as the slurry ratio (liquid: solid) in order to easily depict the behavior of the water absorption of treated RCA with the variations in the slurry ratios and the RHA-lime ratios being used.

It can be clearly seen by observing Figure 4.10 that as the slurry ratio gets thinner the water absorption of the treated RCA reduces and after a minimum value it tends to increase. The thickness of the slurry ratio used to treat the RCA is inversely proportional to the water absorption of the treated RCA in the initial stage, but after the water absorption has obtained a minimum value it will become proportional to the slurry ratio. When the second derivative of the equations of the best fit lines given in Table 4.17, was calculated, they all gave positive values which indicate that the slope is continually getting larger in all cases except the best fit line represented when RHA-lime is 80%: 20%, it gave a negative value. Therefore it can be said that the thickness of the slurry ratio used to treat the RCA is inversely proportional to the water absorption of the treated RCA, when it is treated with various slurry ratios containing 80% and 20% of RHA and lime respectively. By observing Table 4.17 it can be seen that for the rest of the scenarios been tested the minimum water absorption of the treated RCA can be obtained at a slurry ratio between 0.9 and 1.1 (≈1.0).

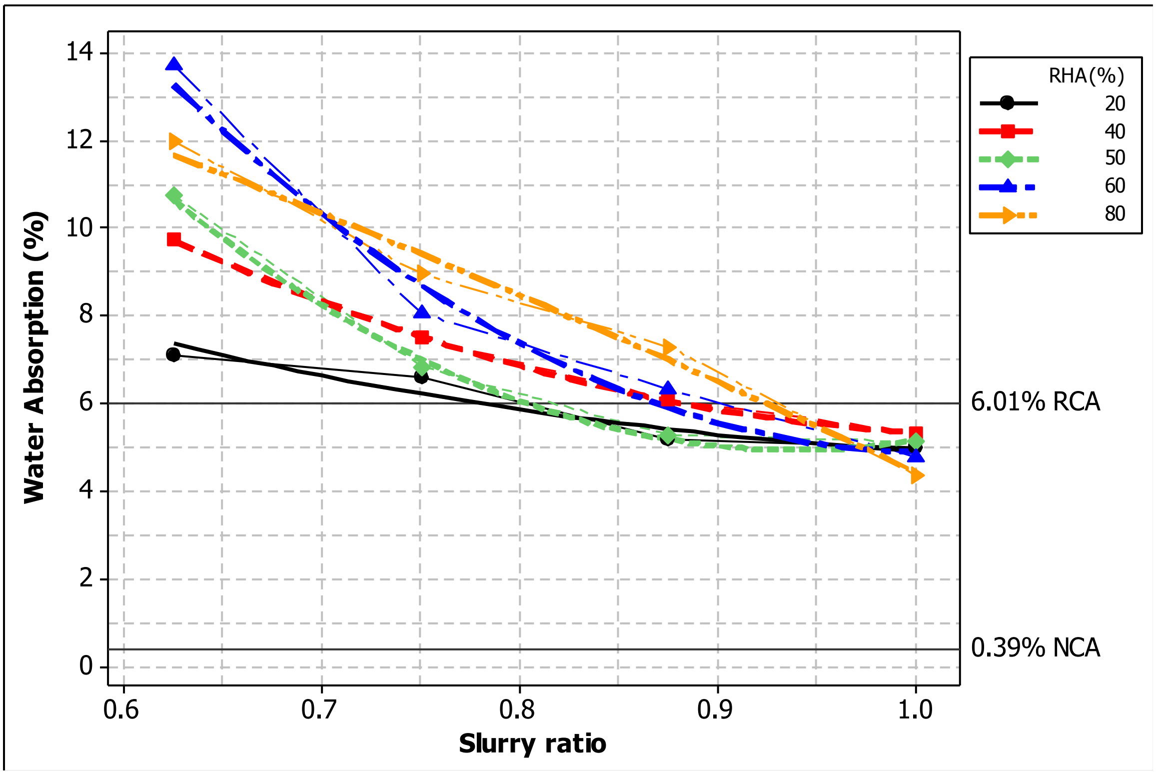


Figure 4. 10: Water Absorption for Varying Slurry Ratios (Liquid: Solid) at Different RHA: Lime Ratios

Table 4. 17: Best Fit Line for Water Absorption for Varying Slurry Ratios (Liquid: Solid) at Different RHA: Lime Ratios

RHA: Lime Ratios	**Equation Of Best Fit Line (Regression Fit) [Quadratic Equation]**	**R^2 (%)**	**Stationary Point (Coordinates)**	
			X	Y
20: 80	[Water Absorption (%)] = 17.86 - 23.30 [Slurry ratio] + 10.37 [Slurry ratio]^2	91.9	1.12	4.77
40: 60	[Water Absorption (%)] = 31.71 - 49.88 [Slurry ratio] + 23.49 [Slurry ratio]^2	100.0	1.06	5.23
50: 50	[Water Absorption (%)] = 55.88 - 108.5 [Slurry ratio] + 57.77 [Slurry ratio]^2	99.7	0.94	4.94
60: 40	[Water Absorption (%)] = 62.92 - 115.1 [Slurry ratio] + 57.04 [Slurry ratio]^2	97.7	1.01	4.85
80: 20	[Water Absorption (%)] = 20.79 - 11.63 [Slurry ratio] - 4.739 [Slurry ratio]^2	98.7	-1.23	27.93

When observing the linear trend lines of the curves as shown by Figure 4.12, it can be clearly seen that for all slurry ratios used to coat the RCA as the RHA percentage present in the slurry is increased the water absorption of the treated RCA increases, except when a slurry ratio of 1.00 is used to coat the RCA. According to Table 4.18, in the case when slurry ratios of 0.625, 0.75 and 0.875 are used to coat RCA the percentage of lime replacement with RHA should not exceed roughly 0.09%, 9.14% and 49.52% respectively in order for the treated RCA to achieve a water absorption value lesser than the untreated RCA (i.e. 6.01%). When observing Figure 4.11 and Table 4.18, it can be seen that when a slurry ratio of 1.000 is used no matter how much lime is replaced with RHA the water absorption of the treated RCA will always be lesser than that of untreated RCA. When considering the curve represented by the slurry ratio 1.000 in Figure 4.11, there may have been some errors when obtaining the water absorption values of the treated RCA. Since even according to many literature when the percentage of replacement of lime with RHA increases the strength of the RHA-lime paste decreases. This was very evident since when a high percentage of RHA was used in all slurries the coating of the treated

RCA was not strong enough, it could have even been easily scraped off by the nail of a finger.

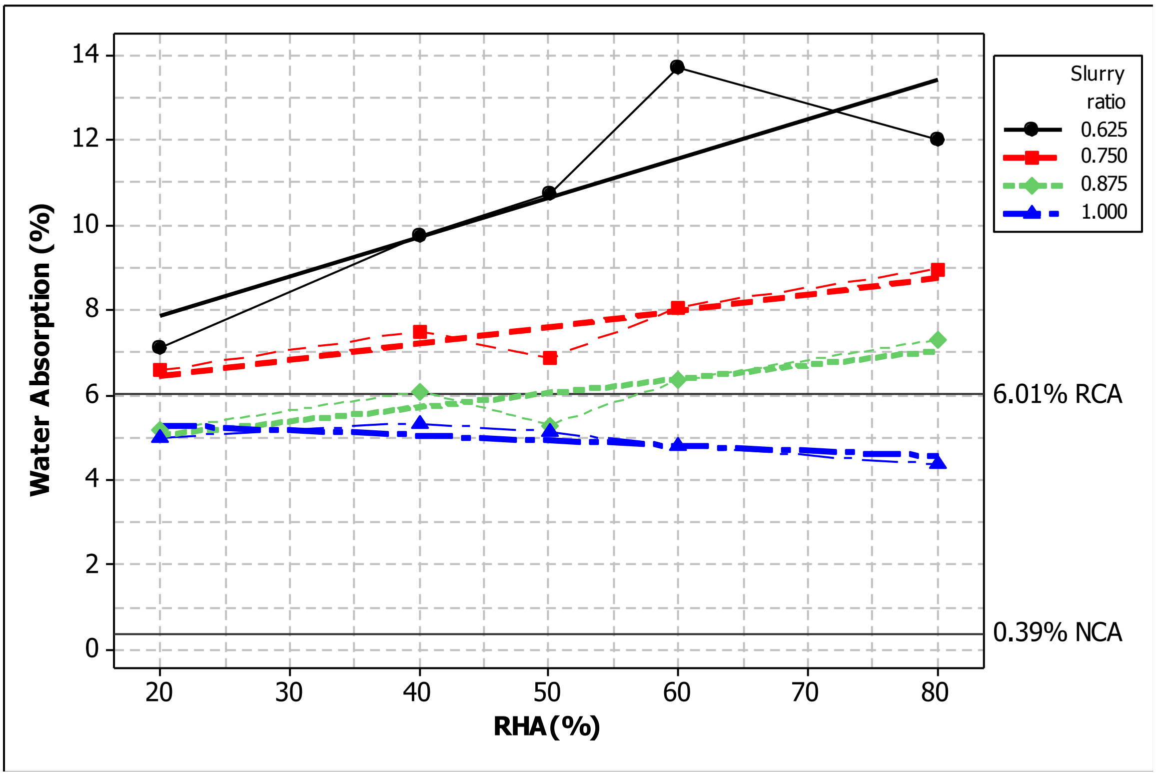


Figure 4. 11: Water Absorption for Varying RHA: Lime Ratios at Different Slurry Ratios (Liquid: Solid)

Table 4. 18: Best Fit Line for Water Absorption for Varying RHA: Lime Ratios at Different Slurry Ratios (Liquid: Solid)

Slurry Ratio (Liquid: Solid)	**Equation of Best Fit Line (Regression Fit) [Linear Equation]**	**R^2 (%)**	**X Coordinates That Intersect The Reference Line 6.01% RCA**
0.625	[Water Absorption (%)] = 6.002 + 0.09298 [RHA (%)]	70.5	0.09
0.75	[Water Absorption (%)] = 5.658 + 0.03850 [RHA (%)]	80.5	9.14
0.875	[Water Absorption (%)] = 4.366 + 0.03320 [RHA (%)]	73.2	49.52
1.000	[Water Absorption (%)] = 5.520 - 0.01220 [RHA (%)]	54.4	-40.16

It should also be highlighted that the water absorption of the treated RCA is very much higher than that of NCA.

Table 4. 19: Water Absorption for Varying RHA: Lime Ratios at Different Slurry (Liquid: Solid) Ratios

Water Absorption of Treated RCA (%) [Mean ± SE]					
RHA (%)	**Lime (%)**	**Slurry Ratios (Liquid: Solid)**			
		0.625	**0.75**	**0.875**	**1.00**
20	**80**	7.11± 0.57	6.58± 0.43	5.17± 0.33	4.98± 0.41
40	**60**	9.73± 0.00	7.49± 0.58	6.07± 0.00	5.32± 0.32
50	**50**	10.74± 0.81	6.84± 0.01	5.27± 0.53	5.12± 0.36
60	**40**	13.70± 0.25	8.06± 0.57	6.32± 0.46	4.77± 0.28
80	**20**	11.98± 0.06	8.95± 0.10	7.30± 0.43	4.35± 0.07

By observing Figure 4.10 and Figure 4.11 it can be stated that the water absorption of the treated RCA is proportional to the percentage of RHA added in to the slurry and is inversely proportional to the slurry ratio.

According to Table 4.20, there is a strong negative correlation between the slurry ratios used to treat RCA and the water absorption of the treated RCA since the correlation coefficient between these two variables are -0.840 (≈1). Furthermore it can be clearly confirmed having a 95% significance interval that the correlation coefficient between the slurry ratios used to treat RCA and the water absorption of the treated RCA is significantly different from zero since the P-Value is 0.000 (<0.05).

Table 4. 20: Correlation Coefficient between Water Absorption, Slurry Ratio and RHA (%)

		Water Absorption	**Slurry Ratios**
Slurry Ratios	Pearson Correlation	-0.840	
	P-Value	0.000	
RHA (%)	Pearson Correlation	0.305	0.000
	P-Value	0.191	1.000

According to Table 4.20, correlation coefficient between the RHA (%) used to treat RCA and the water absorption of the treated RCA is 0.305 (0< 0.305< 1). Hence it cannot be confirmed that there is a strong correlation coefficient between these two variables, but it can be stated that the correlation coefficient between these two variables is positive. Furthermore it can be confirmed having a 80% significance interval that the correlation coefficient between the RHA (%) used to treat RCA and the water absorption of the treated RCA is significantly different from zero since the P-Value is 0.191 (<0.2).

4.2.1.1.2. Relative Density on SSD Basis

According to Figure 4.11 and Figure 4.12, it can be clearly seen that there is a strong negative correlation between the water absorption of the treated RCA and its relative density since the Pearson correlation of the water absorption of the treated RCA and its relative density (SSD basis) is -0.826 (≈1). Hence it can be clearly confirmed having a 95% confidence that the correlation coefficient between the water absorption of the treated RCA and its relative density is significantly different from zero since the P-Value is 0.000 (<0.05). Therefore it can be stated that the water absorption of the treated RCA and its relative density is inversely proportional.

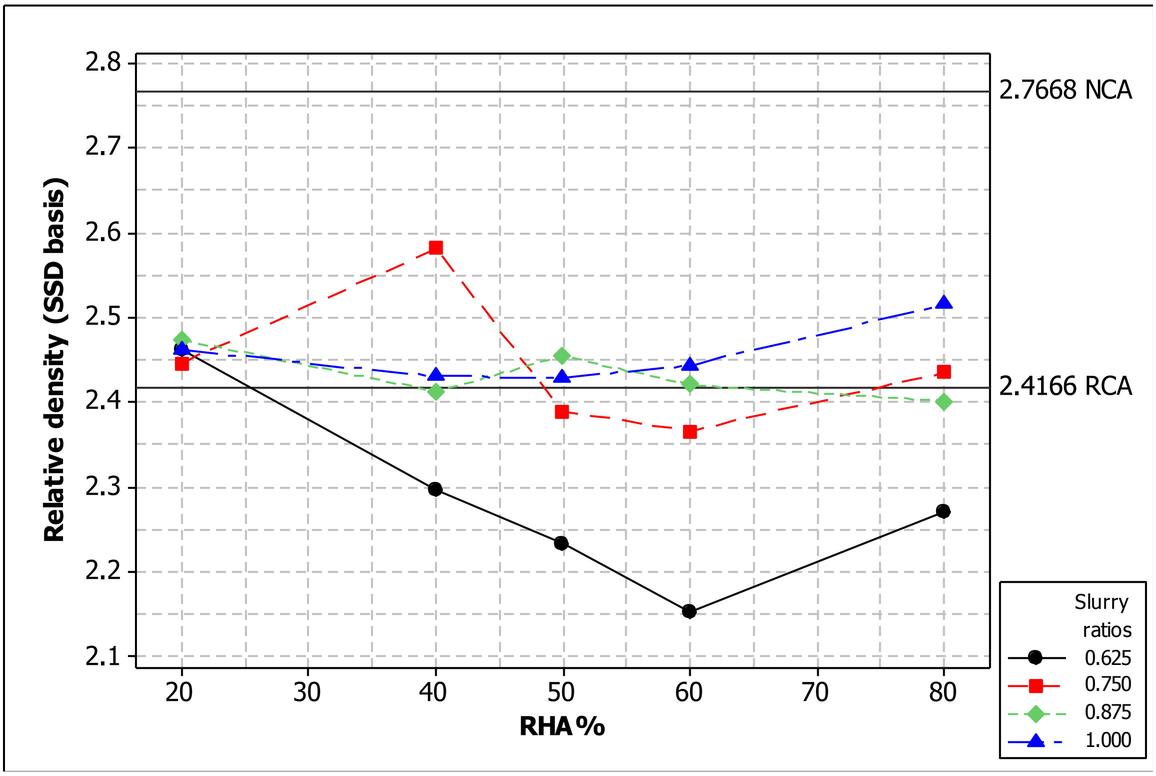


Figure 4. 12: Relative Density (SSD basis) for Varying RHA: Lime Ratios at Different Slurry (Liquid: Solid) Ratios

Table 4. 21: Relative Density (SSD Basis) for Varying RHA: Lime Ratios at Different Slurry (Liquid: Solid) Ratios

Relative Density (SSD Basis) of Treated RCA (%) [Mean ± SE]					
RHA (%)	**Lime (%)**	**Slurry Ratios (Liquid: Solid)**			
		0.625	0.75	0.875	1.00
20	**80**	2.46± 0.02	2.45± 0.02	2.47± 0.01	2.46± 0.02
40	**60**	2.30± 0.00	2.58± 0.25	2.42± 0.00	2.43± 0.02
50	**50**	2.23± 0.01	2.39± 0.01	2.45± 0.02	2.43± 0.02
60	**40**	2.15± 0.03	2.37± 0.01	2.42± 0.02	2.44± 0.01
80	**20**	2.27± 0.00	2.43± 0.01	2.40± 0.02	2.52± 0.00

Even though RCA was treated with RHA: lime slurry all the resultant TRCA's are very much lighter than NCA since all the specific gravity values of TRCA's are lower than that of NCA (= 2.7668).

4.2.1.2. Mortar Cube Strength of Each Slurry Scenario

When observing Figure 4.13 it can be clearly seen that the mortar strength of the mortar cubes made with the slurry ratios of 0.625, 0.75 and 0.875 have achieved a peak at a RHA: lime ratio of 40%: 60%. Furthermore according to the best fit curves shown in Figure 4.13 and Table 4.22, the strength of the mortar cubes at 28 days made with 0.625, 0.75 and 0.875 slurry ratios with varying RHA: lime ratios have obtained maximum strengths when around 33-36% of lime was replaced with RHA. Hence it can be said that the scenario that gives the maximum strength is when a RHA: lime ratio of 33-40%: 60-67% is used. According to Mindess et al., 2002, the pozzolanic reaction between SiO_2 and $Ca(OH)_2$ released from the hydration reaction of cement has a molar ratio of 2: 3 (Mindess, Young & Darwin, 2002). Due to the pozzolanic reaction an excess amount of calcium-silicate-hydrate

($CaO \cdot 2SiO_2 \cdot 8H_2O$) will be produced in the cement paste. This results in the increase in the strength of the cement paste and the porosity in the paste will also reduce since the resultant calcium-silicate-hydrate ($CaO \cdot 2SiO_2 \cdot 8H_2O$) will get deposited in these pores. Hence it is evident why there was a peak in the mortar cube strength made with the slurry ratios 0.625, 0.75 and 0.875. It should be highlighted that the mortar cubes made with 100% of lime all had dissolved at a curing age of 28 days but those made with a mixture of RHA and lime had not. Therefore it can be concluded that the SiO_2 present in the RHA chemically reacts with the $Ca(OH)_2$ present in the lime used.

Pozzolanic reaction:

$3Ca(OH)_2 + 2SiO_2 + 5H_2O \rightarrow 3CaO \cdot 2SiO_2 \cdot 8H_2O$ … (1) (Mindess et al, 2002)
$Ca(OH)_2$: Calcium-hydroxide
SiO_2: Silica
H_2O: Water

$CaO.2SiO_2.8H_2O$: Calcium-silicate-hydrate

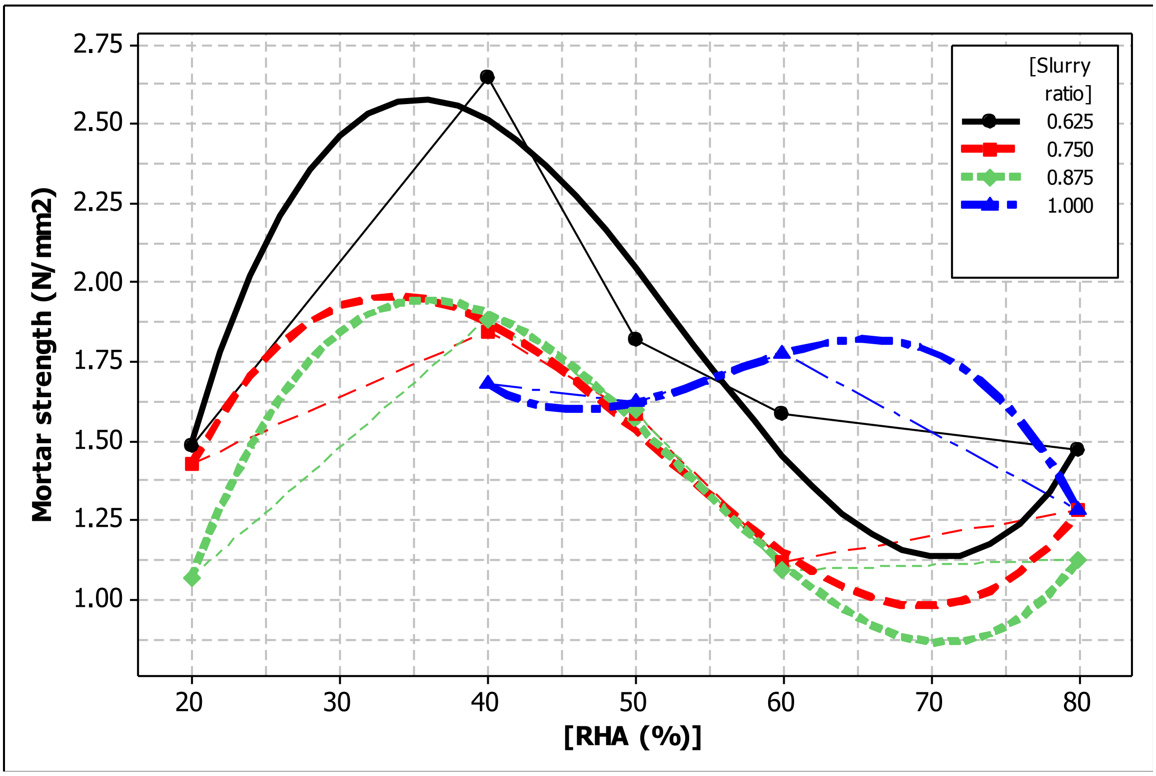


Figure 4. 13: Mortar Cube Strength (N/mm2) at a Curing Age of 28 days for Varying RHA: Lime Ratios at Different Slurry (Liquid: Solid) Ratios

Table 4. 22: Best Fit Line for Mortar Cube Strength for Varying RHA: Lime Ratios at Different Slurry Ratios (Liquid: Solid)

Slurry Ratio (Liquid: Solid)	**Equation of Best Fit Line (Regression Fit) [Cubic Equation]**	**R^2 (%)**	**Stationary Point (Coordinates)**			
			Maxima		**Minima**	
			X	**Y**	**X**	**Y**
0.625	[Mortar strength (N/mm2)] = $- 4.767 + 0.4972$ [RHA (%)] - 0.01052 [RHA (%)]^2 + 0.000066 [RHA (%)]^3	91.1	35.47	2.58	70.79	1.12
0.75	[Mortar strength (N/mm2)] = $- 2.243 + 0.2976$ [RHA (%)] - 0.006560 [RHA (%)]^2 + 0.000042 [RHA (%)]^3	98.5	33.39	1.94	70.74	0.85
0.875	[Mortar strength (N/mm2)] = $- 3.830 + 0.3871$ [RHA (%)] - 0.008121 [RHA (%)]^2 + 0.000051 [RHA (%)]^3	99.6	36.13	1.96	70.03	0.97
1.000	[Mortar strength (N/mm2)] = $11.30 - 0.5489$ [RHA (%)] + 0.01012 [RHA (%)]^2 - 0.000060 [RHA (%)]^3	100.0	66.78	1.91	45.66	1.62

When considering the strengths of the mortar cubes made with the slurry ratio of 1.000 it can be seen that it behaves in an opposite manner when comparing it with the rest of the curves presented in Figure 4.13. This can be mainly due to the excess amount of water present in the slurry. Therefore the mortar cubes made with the slurry ratio 1.000 tends to have more coarse pores hence reducing their strengths. It should also be brought to notice that the mortar cubes made with this slurry having a RHA: lime ratio of 20%: 80% had got dissolved after 28 days of curing.

By observing the mortar cube strength at a curing age of 28 days shown in Table 4.23, it can be seen that the strength values roughly lie within a range of 1.05-2.70 N/mm^2. Hence even though the SiO_2 present in the RHA chemically reacts with the $Ca(OH)_2$ present in the lime the strength gain is very small. This denotes that when RCA it is treated with RHA-lime the coating around the RCA is very weak since its strength is very small. The RHA-lime coating around RCA could be easily removed by the rubbing of the finger nail. This could be detrimental when used in a concrete mix since $Ca(OH)_2$ that gets removed off from the coating will get added in to the concrete mix. Therefore this will cause the concrete made by RCA treated with RHA-lime to be susceptible to acid attack, sulphate penetration and alkaline penetration.

Table 4. 23: Mortar Cube Strength (N/Mm2) at a Curing Age of 28 Days for Varying RHA: Lime Ratios at Different Slurry (Liquid: Solid) Ratios

Mortar Cube Strength (N/Mm2) [Mean ± SE]					
RHA (%)	**Lime (%)**	**Slurry Ratios (Liquid: Solid)**			
		0.625	**0.75**	**0.875**	**1.00**
0	**100**	Dissolved at 28 Days	Dissolved at 28 Days	Dissolved at 28 Days	Dissolved at 28 Days
20	**80**	1.48± 0.04	1.43± 0.01	1.07± 0.26	Dissolved At 28 Days
40	**60**	2.65± 0.14	1.85± 0.03	1.88± 0.05	1.68± 0.07
50	**50**	1.82± 0.23	1.59± 0.07	1.60± 0.00	1.62± 0.08
60	**40**	1.58± 0.01	1.12± 0.00	1.09± 0.10	1.78± 0.03
80	**20**	1.47± 0.08	1.28± 0.06	1.13± 0.04	1.28± 0.06

4.2.2. Treatment of RCA with Ground Rice Husk Ash (RHA) - Cement Slurry

4.2.2.1. Specific Gravity and Water Absorption of the Coated RCA

4.2.2.1.1. Water Absorption

4.2.2.1.1.1. The Effect the Slurry has on the Water Absorption of the Treated RCA

The correlation coefficient between the slurry ratio and the water absorption of the treated RCA is -0.448 having a P-value of 0.006 at a 5% significance level. It can be confirmed with a 95% confidence that the correlation coefficient between the slurry ratio and the water absorption of the treated RCA is significantly different from zero since the P-value is 0.006 (<0.05). Furthermore it can be stated that there is a negative correlation between the slurry ratio and the water absorption of the treated RCA for the tested scenarios. According to Figure 4.14, it can be observed that the water absorption of the treated RCA reduces as the slurry gets thinner this confirms the negative value of the Pearson correlation coefficient but after it reaches a minimum point it starts to increase. It should be noted that slurries containing only cement have been discussed here. Hence the effect of RHA on the reduction of the water absorption of the treated RCA cannot be discussed here.

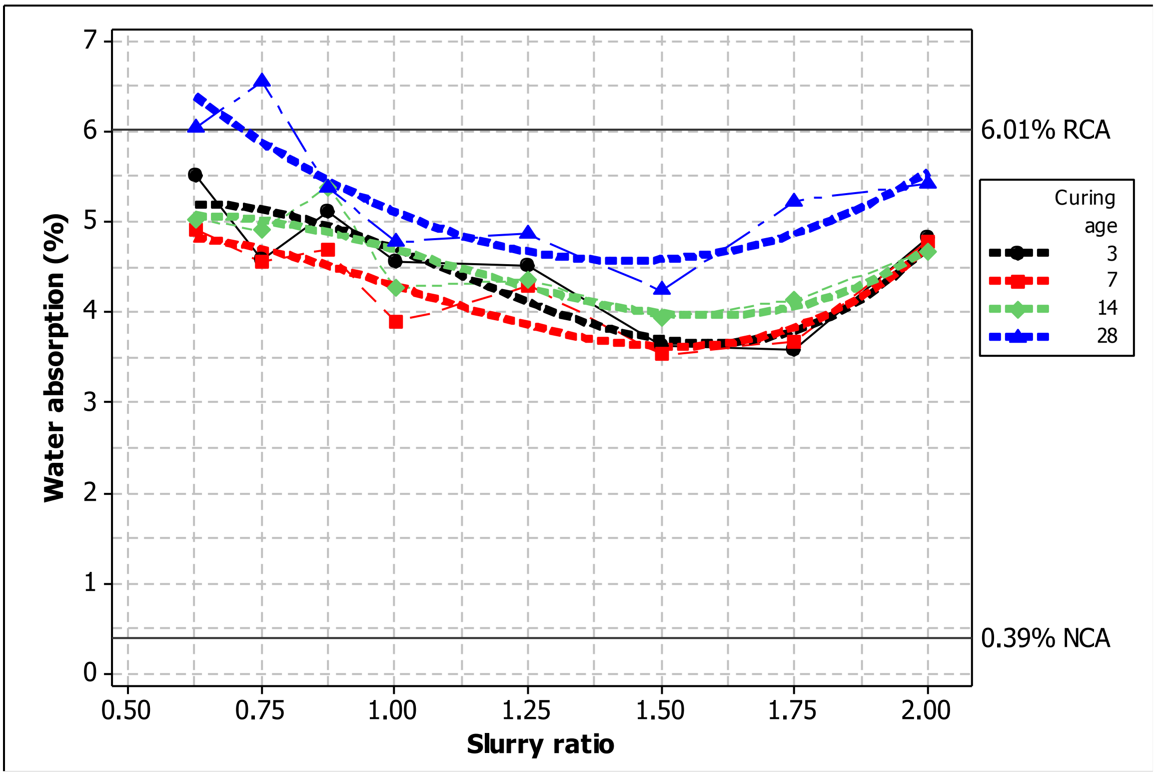


Figure 4. 14: Water Absorption of Treated RCA Treated with Varying Slurry (Liquid: Solid) ratios for RHA: Cement ratio of 0: 100 (%:%) at varying curing ages

It can be seen that there is a reduction in the water absorption of the aggregates due to the treatment method been used. The only chemical reaction that we can be sure of is the hydration reaction of cement. The fine products of hydration will then get deposited in the pores and micro cracks present on the surface of the RCA or even on the surface of RCA depending on the thickness of the slurry been used to coat the

RCA. That is there is a significant reduction in the water absorption of RCA due to the treatment method been used. When analyzing Figure 4.14, the only factor that has been varied when considering the slurry ratio used to treat RCA will be its thickness. When the slurry gets thinner its viscosity reduces. Therefore its flow-ability increases and its ability to penetrate in to the pores and micro cracks present on the surface of the RCA increases, but as the slurry gets very thin the ability of the cement particles to get deposited into these pores and micro fissure become very low since its concentration is very low. When the slurry used to coat RCA gets thicker it will give a very thick coating around the surface of the aggregates. When thick slurries are used even though the hydration reaction of cement occurs on the surface of the RCA the resultant products will not get deposited in to the pores and micro fissures present on the surface of the RCA and furthermore due to the loss of $Ca(OH)_2$ from the cement paste coating more pores would have been formed on the coating itself hence increasing the water absorption of the TRCA.

The correlation coefficient between the age of curing and the water absorption of the treated RCA is 0.441 having a P-value of 0.007. It can be confirmed with a 95% confidence that the correlation coefficient between the age of curing and the water absorption of the treated RCA is significantly different from zero since the P-value is 0.007 (<0.05). Furthermore it can be stated that there is a positive correlation between the age of curing and the water absorption of the treated RCA for the tested scenarios. Figure 4.14 demonstrates that when the age of curing increases the water absorption of the treated RCA also increases. According to Table 4.24, the minimum water absorption (=3.61%) was obtained at a curing age of 7 days. Furthermore when observing Figure 4.14, it can be distinctively seen that in most cases the water absorption is lowest at a curing age of 7 days. Furthermore the water absorption of the treated RCA obtained at a curing age of 3 days and 14 days in all scenarios are greater than that obtained at a curing age of 7 days. But it should be highlighted that as the slurry gets thinner than 1.50 the variation in the water absorption of treated RCA after curing ages of 3 days and 7days is negligible.

Table 4. 24: Best Fit Lines for the Plotted Data Shown in Figure 4.14

Curing Age (Days)	**Equation of Best Fit Line (Regression Fit) [Cubic Equation]**	**R^2 (%)**	**Stationary Point (Coordinates)**			
			Maxima		**Minima**	
			X	**Y**	**X**	**Y**
3	[Water absorption (%)] = 2.237 + 10.70 [Slurry ratio] - 11.77 [Slurry ratio]^2 + 3.518 [Slurry ratio]^3	78.5	0.64	5.19	1.59	3.64
7	[Water absorption (%)] = 3.380 + 6.177 [Slurry ratio] - 7.787 [Slurry ratio]^2 + 2.516 [Slurry ratio]^3	77.3	0.54	4.84	1.53	3.61
14	[Water absorption (%)] = 3.147 + 7.121 [Slurry ratio] - 7.988 [Slurry ratio]^2 + 2.408 [Slurry ratio]^3	73.2	0.62	5.07	1.59	3.95
28	[Water absorption (%)] = 9.990 - 7.11 [Slurry ratio] + 2.01 [Slurry ratio]^2 + 0.217 [Slurry ratio]^3	73.7	-7.61	84.87	1.44	4.57

When analyzing the best fit curves presented in Figure 4.14 and Table 4.24, the minimum water absorption of treated RCA is obtained at a curing of 3 to 7 days. The water absorption of the TRCA is lowest, when it is soaked for a curing age of 7 days. Therefore when RCA is treated with varying slurry (Liquid: Solid) ratios containing 100% of cement its best not to cure the treated RCA beyond 7 days in order to achieve the maximum reduction in its water absorption. Furthermore by analyzing Table 4.24, it can also be stated that when the RCA is treated with slurry containing 100% of cement, a minimum water absorption of the TRCA can be achieved when it is treated with a slurry ratio having a range of 1.5-1.6.

Table 4. 25: Water Absorption of Treated RCA with Varying Slurry (Liquid: Solid) Ratios for RHA: Cement Ratio of 0: 100 (%:%) at Varying Curing Ages

Water Absorption of Treated RCA (%) [Mean ± SE]								
Curing Age (Days)	**Slurry Ratio (Liquid: Solid)**							
	0.625	**0.75**	**0.875**	**1.00**	**1.25**	**1.50**	**1.75**	**2.00**
3	5.51± 0.15	4.58± 0.15	5.12± 0.16	4.56± 0.38	4.50± 0.03	3.61± 0.02	3.58± 0.02	4.83± 0.29
7	4.91± 0.16	4.55± 0.36	4.68± 0.05	3.88± 0.13	4.29± 0.01	3.53± 0.09	3.68± 0.05	4.78± 0.58
14	5.03± 0.16	4.90± 0.17	5.38± 0.10	4.26± 0.21	4.18± 0.02	3.92± 0.12	4.13± 0.04	4.67± 0.57
28	6.04± 0.59	6.54± 0.15	5.38± 0.11	4.77± 0.00	4.86± 0.02	4.23± 0.05	5.22± 0.13	5.42± 0.57

The test results presented in the Figure 4.15, Figure 4. 16 and Figure 4.17, demonstrates the effects the replacement of cement with RHA and the thickness of the slurry will have on the water absorption of the treated RCA.

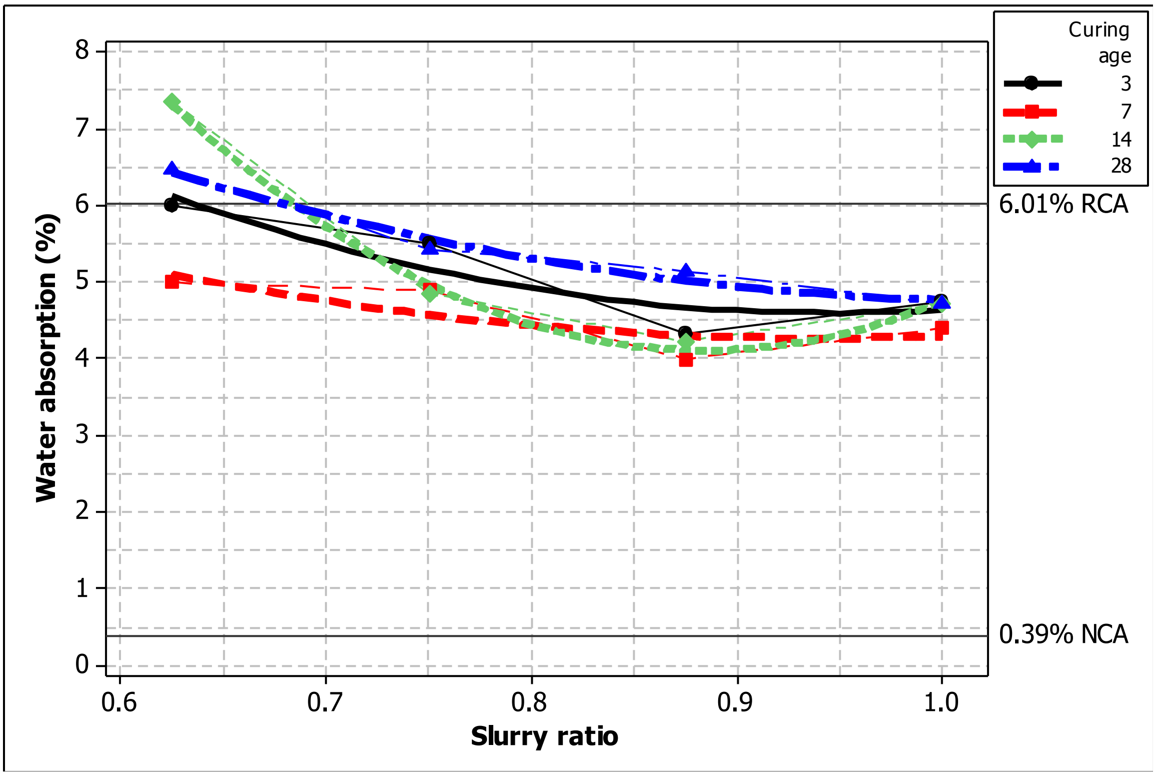


Figure 4. 15: Water Absorption of Treated RCA that had been treated with Varying Slurry (Liquid: Solid) Ratios for RHA: Cement Ratio of 20: 80 (%:%) at Varying Curing Ages

The correlation coefficient between the slurry ratio and the water absorption of the treated RCA is -0.564 having a P-value of 0.004. It can be confirmed with a 95% confidence that the correlation coefficient between the slurry ratio and the water absorption of the treated RCA is significantly different from zero since the P-value is 0.004 (<0.05). Furthermore it can be stated that there is a negative correlation between the slurry ratio and the water absorption of the treated RCA for the tested scenarios. According to Figure 4.15, it can be observed that the water absorption of the treated RCA reduces as the slurry gets thinner this confirms the negative value of the Pearson correlation coefficient but after it reaches a minimum point it starts to increase.

According to Figure 4.15 and Table 4.27, it can be seen that there is a reduction in the water absorption of the aggregates due to the treatment method been used.

Furthermore by analyzing Table 4.26, it can also be stated that when the RCA is treated with slurry containing a RHA: Cement ratio of 20%: 80% a minimum water absorption of the TRCA can be achieved when it is treated with a slurry ratio having a range of 0.85-1.05. But when the RCA is treated with slurry that contains only cement the minimum water absorption of treated RCA is obtained when the slurry ratio is between 1.5-1.6.

Table 4. 26: Best Fit Lines for the Plotted Data Shown in Figure 4.15

<table>
<tr><th rowspan="2">Curing Age (Days)</th><th rowspan="2">Equation of Best Fit Line (Regression Fit) [Quadratic Equation]</th><th rowspan="2">R^2 (%)</th><th colspan="4">Stationary Point (Coordinates)</th></tr>
<tr><th colspan="2">X</th><th colspan="2">Y</th></tr>
<tr><td>3</td><td>[Water absorption mean (%)] = 17.75 - 27.78 [Slurry ratio] + 14.68 [Slurry ratio]^2</td><td>84.7</td><td colspan="2">0.95</td><td colspan="2">4.61</td></tr>
<tr><td rowspan="4">7</td><td>[Water absorption mean (%)] = 11.67 - 15.72 [Slurry ratio] + 8.35 [Slurry ratio]^2</td><td>66.4</td><td colspan="2">0.94</td><td colspan="2">4.27</td></tr>
<tr><td colspan="2" rowspan="2">Equation of best fit line (Regression fit) [Cubic equation]</td><th colspan="2">Minima</th><th colspan="2">Maxima</th></tr>
<tr><th>X</th><th>Y</th><th>X</th><th>Y</th></tr>
<tr><td>[Water absorption (%)] = - 79.16 + 331.1 [Slurry ratio] - 425.5 [Slurry ratio]^2 + 178.0 [Slurry ratio]^3</td><td>100</td><td>0.92</td><td>3.92</td><td>0.67</td><td>5.21</td></tr>
<tr><td>14</td><td>[Water absorption mean (%)] = 41.36 - 84.27 [Slurry ratio] + 47.65 [Slurry ratio]^2</td><td>99.5</td><td colspan="2">0.88</td><td colspan="2">4.10</td></tr>
<tr><td>28</td><td>[Water absorption mean (%)] = 15.24 - 20.18 [Slurry ratio] + 9.701 [Slurry ratio]^2</td><td>97.6</td><td colspan="2">1.04</td><td colspan="2">4.75</td></tr>
</table>

The correlation coefficient between the age of curing and the water absorption of the treated RCA is 0.441 having a P-value of 0.043. It can be confirmed with a 95% confidence that the correlation coefficient between the age of curing and the water absorption of the treated RCA is significantly different from zero since the P-value is 0.043 (<0.05). Furthermore it can be stated that there is a positive correlation between the age of curing and the water absorption of the treated RCA for the tested scenarios. Figure 4.15 demonstrates that when the age of curing increases the water absorption of the treated RCA also increases. According to Table 4.26, the minimum water absorption (= 4.10%) was obtained at a curing age of 14 days. When 100% of cement was used in the slurry the lowest water absorption was obtained at a curing age of 7 days but with the replacement of cement with RHA the lowest was obtained at a curing age of 14 days. It can be due to the pozzolanic reaction since it is slower than the hydration reaction of cement hence the minimum water absorption of the treated RCA was obtained at a later curing age. On the contrary when observing Figure 4.15, it can be distinctively seen that in most cases the water absorption is lowest at a curing age of 7 days than a curing age of 14 days. Furthermore the water absorption of the treated RCA obtained at a curing age of 3 days in all scenarios is greater than that obtained at a curing age of 7 days. A similar behavioral pattern in the water absorption of the treated RCA was observed when the slurry that was used to coat RCA contained only cement. When analyzing the best fit curves presented in Figure 4.15 and Table 4.26, the minimum water absorption of treated RCA was obtained at a curing of 7 to 14 days. But in most scenarios the water absorption of the TRCA is lowest, when it is cured for a curing age of 7 days. Therefore when RCA is treated with varying slurry (Liquid: Solid) ratios containing a RHA: Cement content of 20%: 80% its best not to cure the treated RCA beyond 7 days in order to achieve the maximum reduction in its water absorption.

Table 4. 27: Water Absorption of Treated RCA Treated With Varying Slurry (Liquid: Solid) Ratios for RHA: Cement Ratio of 20: 80 (%:%) at Varying Curing Ages

Water Absorption of Treated RCA (%) [Mean ± SE]				
Curing Age (Days)	**Slurry Ratio (Liquid: Solid)**			
	0.625	**0.75**	**0.875**	**1.00**
3	6.00± 0.19	5.51± 0.16	4.34± 0.09	4.76± 0.23
7	5.00± 0.12	4.89± 0.09	3.99± 0.25	4.40± 0.01
14	7.35± 0.81	4.85± 0.21	4.23± 0.59	4.71± 0.29
28	6.47± 0.02	5.43± 0.92	5.15± 0.32	4.72± 0.32

The correlation coefficient between the slurry ratio and the water absorption of the treated RCA is -0.523 having a P-value of 0.015. It can be confirmed with a 95% confidence that the correlation coefficient between the slurry ratio and the water absorption of the treated RCA is significantly different from zero since the P-value is 0.015 (<0.05). Furthermore it can be stated that there is a negative correlation between the slurry ratio and the water absorption of the treated RCA for the tested scenarios. According to Figure 4.16, it can be observed in most scenarios that the water absorption of the treated RCA reduces as the slurry gets thinner this confirms the negative value of the Pearson correlation coefficient but after it reaches a minimum point it starts to increase.

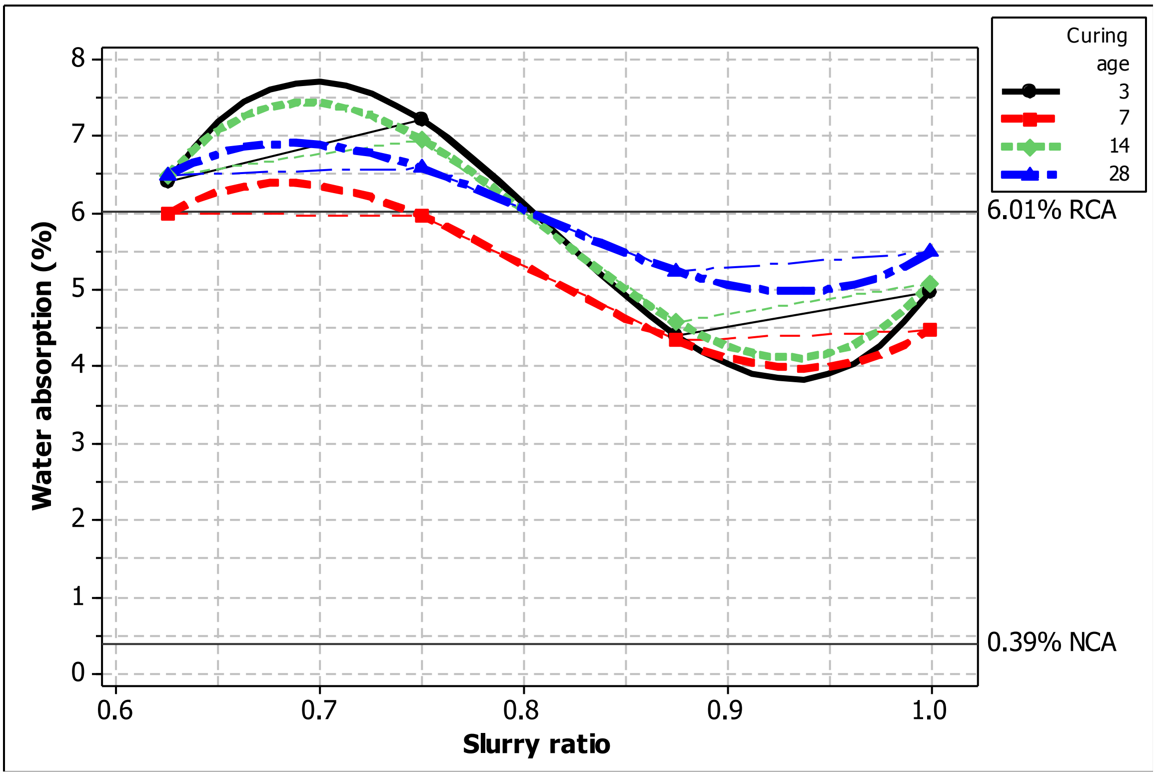


Figure 4. 16: Water Absorption of Treated RCA that had been treated with Varying Slurry (Liquid: Solid) Ratios for RHA: Cement Ratio of 40: 60 (%:%) at Varying Curing Ages

According to Figure 4.16 and Table 4.29, it can be seen that there is a reduction in the water absorption of the aggregates due to the treatment method used.

Furthermore by analyzing Table 4.28, it can also be stated that when the RCA is treated with slurry containing a RHA: Cement ratio of 40%: 60% a minimum water absorption of the TRCA can be achieved when it is treated with a slurry ratio having a range of 0.90-0.95. This range tallies with the slurry ratio range (i.e. 0.85-1.05) that gives the minimum water absorption of the TRCA when it was treated with slurry containing a RHA: Cement ratio of 20%: 80%. But when the RCA is treated with slurry that contains only cement the minimum water absorption of treated RCA is obtained when the slurry ratio is between 1.5-1.6.

Table 4. 28: Best Fit Lines for the Plotted Data Shown in Figure 4.16

Curing Age (Days)	**Equation of Best Fit Line (Regression Fit) [Cubic Equation]**	**R^2 (%)**	**Stationary Point (Coordinates)**			
			Maxima		**Minima**	
			X	**Y**	**X**	**Y**
3	[Water absorption (%)] = - 295.4 + 1159 [Slurry ratio] - 1453 [Slurry ratio]^2 + 594.5 [Slurry ratio]^3	100.0	0.70	7.84	0.93	3.96
7	[Water absorption (%)] = - 135.0 + 547.7 [Slurry ratio] - 694.1 [Slurry ratio]^2 + 285.8 [Slurry ratio]^3	100.0	0.68	6.35	0.94	3.91
14	[Water absorption (%)] = - 238.5 + 944.2 [Slurry ratio] - 1188 [Slurry ratio]^2 + 487.8 [Slurry ratio]^3	100.0	0.69	7.64	0.93	4.47
28	[Water absorption (%)] = - 120.6 + 492.8 [Slurry ratio] - 623.6 [Slurry ratio]^2 + 256.9 [Slurry ratio]^3	100.0	0.69	6.93	0.93	4.99

According to Figure 4.16 and Table 4.29, it can be seen that there is a reduction in the water absorption of the aggregates due to the treatment method used.

Furthermore by analyzing Table 4.28, it can also be stated that when the RCA is treated with slurry containing a RHA: Cement ratio of 40%: 60% a minimum water absorption of the TRCA can be achieved when it is treated with a slurry ratio having a range of 0.90-0.95. This range tallies with the slurry ratio range (i.e. 0.85-1.05) that gives the minimum water absorption of the TRCA when it was treated with slurry containing a RHA: Cement ratio of 20%: 80%. But when the RCA is treated with slurry that contains only cement the minimum water absorption of treated RCA is obtained when the slurry ratio is between 1.5-1.6.

The correlation coefficient between the age of curing and the water absorption of the treated RCA is 0.129 having a P-value of 0.577. It can't be confirmed with a 90% confidence that the correlation coefficient between the age of curing and the water absorption of the treated RCA is significantly different from zero since the P-value is 0.577 (>0.10). This may indicate that when the cement replacement with RHA is increased up to 40%, the water absorption of the treated RCA is not strongly correlated with the age of curing. But it can be stated that there is a positive correlation between the age of curing and the water absorption of the treated RCA for the tested scenarios. According to Figure 4.16 it can be clearly seen that until a slurry ratio of 0.875 as the age of curing increases the water absorption of the treated RCA also increases but beyond the slurry ratio 0.875 it can be seen that there is no distinct effect on the water absorption of the treated RCA due to the age of curing especially when considering the curing ages of 3 days, 7 days and 14 days. Furthermore the water absorption of the treated RCA when cured for a curing age of 3 days and 14 days do not show a large variation.

According to Table 4.28, the minimum water absorption (=3.91%) was obtained at a curing age of 7 days. When 100% of cement was used in the slurry the lowest water absorption was also obtained at a curing age of 7 days. When observing Figure 4.16, it can be distinctively seen in all the cases been tested that the water absorption is lowest at a curing age of 7 days than any other curing age been tested. Furthermore the water absorption of the treated RCA obtained at a curing age of 3 and 14 days in all scenarios are greater than that obtained at a curing age of 7 days. A similar behavioral pattern in the water absorption of the treated RCA was observed when the slurry that was used to coat RCA contained only cement. When analyzing the best fit curves presented in Figure 4.16 and Table 4.28, the minimum water absorption of treated RCA was obtained at a curing of 7 days. Therefore when RCA is treated with varying slurry (Liquid: Solid) ratios containing a RHA: Cement content of 40%: 60% its best not to cure the treated RCA beyond 7 days in order to achieve the maximum reduction in its water absorption.

Table 4. 29: Water Absorption of Treated RCA Treated With Varying Slurry (Liquid: Solid) Ratios for RHA: Cement Ratio of 40: 60 (%:%) at Varying Curing Ages

Water Absorption Of Treated RCA (%) [Mean ± SE]				
Curing Age (Days)	**Slurry Ratio (Liquid: Solid)**			
	0.625	**0.75**	**0.875**	**1.00**
3	6.40± 0.13	7.20± 0.05	4.40± 0.00	4.97± 0.19
7	5.98± 0.25	5.95± 0.10	4.33± 0.01	4.47± 0.01
14	6.48± 0.10	6.94± 0.05	4.57± 0.01	5.07± 0.04
28	6.49± 0.19	6.57± 0.07	5.23± 0.01	5.48± 0.14

The correlation coefficient between the slurry ratio and the water absorption of the treated RCA is -0.853 having a P-value of 0.000. It can be confirmed with a 95% confidence that the correlation coefficient between the slurry ratio and the water absorption of the treated RCA is significantly different from zero since the P-value is 0.000 (<0.05). Furthermore it can be stated that there is a strong negative correlation between the slurry ratio and the water absorption of the treated RCA for the tested scenarios since the correlation coefficient between the slurry ratio and the water absorption of the treated RCA is -0.853 (≈1). According to Figure 4.17, it can be observed in most scenarios that the water absorption of the treated RCA reduces as the slurry gets thinner this confirms the negative value of the Pearson correlation coefficient but after it reaches a minimum point it starts to increase.

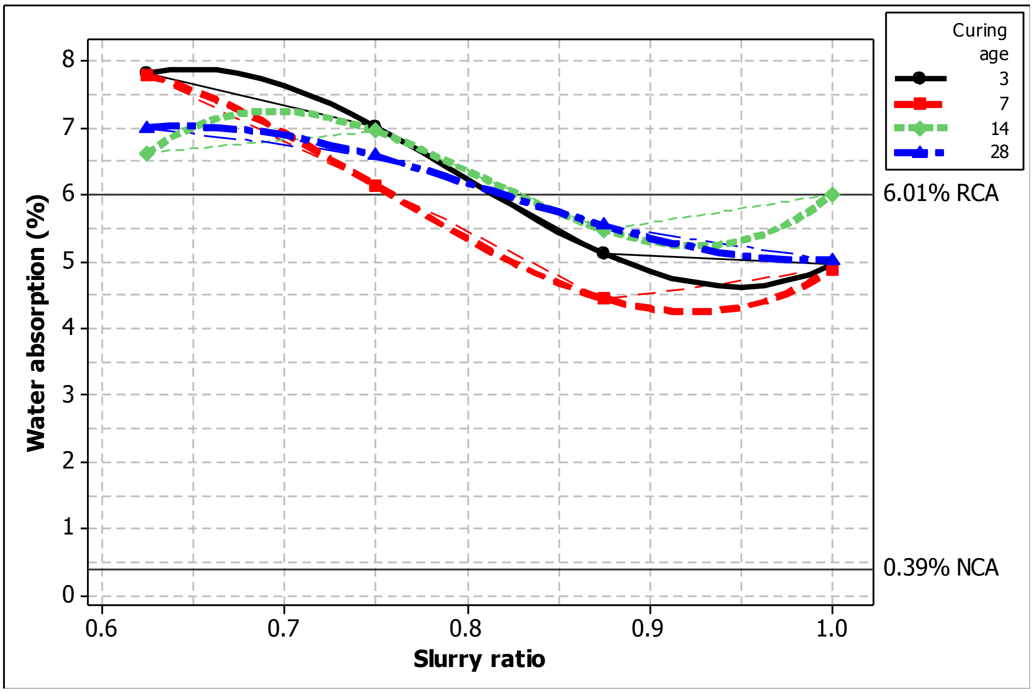


Figure 4. 17: Water Absorption of Treated RCA that had been treated with Varying Slurry (Liquid: Solid) Ratios for RHA: Cement Ratio of 50: 50 (%:%) at Varying Curing Ages

According to Figure 4.17 and Table 4.31, it can be seen that there is a reduction in the water absorption of the aggregates due to the treatment method used.

Furthermore by analyzing Table 4.30, it can also be stated that when the RCA is treated with slurry containing a RHA: Cement ratio of 50%: 50% a minimum water absorption of the TRCA can be achieved when it is treated with a slurry ratio having a range of 0.9-1.0. This range tallies with the slurry ratio range of 0.85-1.05 and 0.90-0.95 that gave the minimum water absorption of the TRCA when it was treated with slurries containing a RHA: Cement ratio of 20%: 80% and 40%: 60% respectively. But it should be reminded that when the RCA was treated with slurry that contained only cement the minimum water absorption of treated RCA was obtained when the slurry ratio is between 1.5-1.6.

Table 4. 30: Best Fit Lines for The Plotted Data Shown in Figure 4.17

Curing Age (Days)	**Equation of Best Fit Line (Regression Fit) [Cubic Equation]**	R^2 **(%)**	**Stationary Point (Coordinates)**			
			Maxima		**Minima**	
			X	**Y**	**X**	**Y**
3	[Water absorption (%)] = - 105.6 + 452.7 [Slurry ratio] - 587.0 [Slurry ratio]^2 + 244.8 [Slurry ratio]^3	100.0%	0.65	7.88	0.95	4.58
7	[Water absorption (%)] = - 60.65 + 298.7 [Slurry ratio] - 418.6 [Slurry ratio]^2 + 185.5 [Slurry ratio]^3	100.0%	0.58	7.97	0.92	4.30
14	[Water absorption (%)] = - 155.0 + 623.9 [Slurry ratio] - 787.2 [Slurry ratio]^2 + 324.3 [Slurry ratio]^3	100.0%	0.69	7.24	0.92	5.23
28	[Water absorption (%)] = - 40.56 + 188.5 [Slurry ratio] - 241.4 [Slurry ratio]^2 + 98.47 [Slurry ratio]^3	100.0%	0.64	7.02	0.99	5.00

The correlation coefficient between the age of curing and the water absorption of the treated RCA is 0.181 having a P-value of 0.488. It can't be confirmed with a 90% confidence that the correlation coefficient between the age of curing and the water absorption of the treated RCA is significantly different from zero since the P-value is 0.488 (>0.10). This may indicate that when the cement replacement with RHA is increased up to 50%, the water absorption of the treated RCA is not strongly correlated with the age of curing. A similar behavioral pattern was observed when analyzing the correlation coefficient between the age of curing and the water absorption of the treated RCA when the cement replacement with RHA was up to 40%. But it can be stated that there is a positive correlation between the age of curing and the water absorption of the treated RCA for the tested scenarios. It can be said that, the effect the age of curing has on the water absorption of the treated RCA reduces with the increase of RHA present in the slurry.

According to Figure 4.17, the water absorption of the treated RCA when cured for a curing age of 3 days and 7 days show a similar variation and as the slurry gets thicker (i.e. 0.625) and the slurry gets thinner (i.e. 1.000) the water absorption values of the treated RCA tend to be similar. Furthermore the water absorption of the treated RCA when cured for a curing age of 14 days and 28 days do not show a large variation with one another.

According to Table 4.30, the minimum water absorption (=4.30%) was obtained at a curing age of 7 days. When 100% of cement was used in the slurry the lowest water absorption was also obtained at a curing age of 7 days. When observing Figure 4.16, it can be distinctively seen in all the cases been tested that the water absorption is lowest at a curing age of 7 days than any other curing age been tested. Furthermore the water absorption of the treated RCA obtained at a curing age of 3 and 14 days in most of the scenarios analyzed are greater than that obtained at a curing age of 7 days. Similar behavioral patterns were observed in the water absorption of the treated RCA for all slurry ratios been used to coat RCA. When analyzing the best fit curves presented in Figure 4.17 and Table 4.30, the minimum water absorption of treated RCA was obtained at a curing of 7 days. Therefore when RCA is treated with varying slurry (Liquid: Solid) ratios containing a RHA: Cement content of 50%: 50% its best not to cure the treated RCA beyond 7 days in order to achieve the maximum reduction in its water absorption.

Table 4. 31: Water Absorption of Treated RCA Treated With Varying Slurry (Liquid: Solid) Ratios for RHA: Cement Ratio of 50: 50 (%:%) at Varying Curing Ages

Water Absorption of Treated RCA (%) [Mean ± SE]				
Curing Age (Days)	**Slurry Ratio (Liquid: Solid)**			
	0.625	**0.75**	**0.875**	**1.00**
3	7.80± 0.09	7.02± 0.12	5.11± 0.30	4.94± 0.09
7	7.78± 0.76	6.13± 0.16	4.44± 0.12	4.88± 0.02
14	6.62± 0.07	6.94± 0.05	5.47± 0.01	6.00± 0.05
28	7.00± 0.72	6.57± 0.07	5.53± 0.00	5.02± 0.13

According to Figure 4.15, Figure 4.16 and Figure 4.17 and Table 4.27, Table 4.29 and Table 4.31 that presents the effect the variation in the thickness of the slurries used to coat RCA has on the water absorption of the treated RCA, it can be seen that there is a reduction in the water absorption of the aggregates due to the treatment method been used.

Mainly there are two chemical reactions that occur when a mixture of RHA and cement is present. They are the hydration reaction of cement and the pozzolanic reaction between the SiO_2 present in the RHA and the $Ca(OH)_2$ produced by the hydration reaction of cement. The pozzolanic reaction in concrete has several steps. When Portland cement is mixed with water, the Tri-calcium-silicate (C_3S) and Di-calcium-silicates (C_2S) present in the Portland cement begins to react with water and will produce Calcium-silicate-hydrates (C-S-H) and Calcium-hydroxide ($Ca(OH)_2$). The Calcium-silicate-hydrates (C-S-H) is largely responsible for the strength development in the cement paste. The alkalinity of the water also known as the pore fluid increases to a pH 13 or a higher level. Due to the hydration reaction of cement and the high level of pH in the water the pozzolanic reaction between the RHA and $Ca(OH)_2$ produced by the hydration reaction of cement will be triggered. Here the high level of pH present in the water will cause the silicate network structure present in the RHA to break down in to finer units. These fine SiO_2 units will then react with the $Ca(OH)_2$ to produce more C-S-H binder. The $Ca(OH)_2$ present in the cement paste is its main point of weakness since it is easily prone to certain forms of chemical reactions that can cause adverse effects on the cement paste and it has no strength gaining properties. Therefore due to the pozzolanic reaction $Ca(OH)_2$ will be converted in to additional C-S-H binder which will then be deposited in the pore spaces. Therefore a much dense cement paste matrix can be achieved hence a reduced permeability, increased strength and increased long-term durability can be obtained (Vitro Minerals, 2015).

The fine products produced by the hydration reaction of cement and the pozzolanic reaction will then get deposited in the pores and micro cracks present on the surface of RCA or will get clumped on the surface of RCA depending on the thickness of the slurry been used to coat the RCA. When individually analyzing Figures 4.15 to 4.17, the only factor that has been varied when considering the slurry ratio used to treat RCA will be its thickness. It should be highlighted that the RHA-cement content used in the scenarios depicted in Figures 4.15 to 4.17, vary as 20%: 80%, 40%: 60%

and 50%: 50%. But the effect it has on the water absorption cannot be directly interpreted hence the effect the amount of cement been replaced by RHA will be discussed later.

When the slurry gets thinner its viscosity reduces. Therefore its flow-ability increases and its ability to penetrate in to the pores and micro cracks present on the surface of the RCA increases, but as the slurry gets very thin the ability of the cement and RHA particles to get deposited into these pores and micro fissure become very low since its concentration is very low. When the slurry used to coat RCA gets thicker it will give a very thick coating around the surface of the aggregates. When thick slurries are used even though the hydration reaction of cement and pozzolanic reaction of RHA occurs on the surface of the RCA the resultant products will not get deposited in to the pores and micro fissures present on the surface of the RCA and furthermore due to the loss of $Ca(OH)_2$ from the RHA-cement paste more pores would have been formed on the coating itself hence increasing the water absorption of the TRCA.

4.2.2.1.1.2. The Effect of the Percentage of Cement Replaced With RHA in the Slurry to Treat RCA Has on Its Water Absorption

The correlation coefficient between the percentage of cement been replaced by RHA and the water absorption of the treated RCA is 0.844 having a P-value of 0.000. It can be confirmed with a 95% confidence that the correlation coefficient between the percentage of cement been replaced by RHA and the water absorption of the treated RCA is significantly different from zero since the P-value is 0.000 (<0.05). Furthermore it can be stated that there is a strong positive correlation between the percentage of cement been replaced by RHA and the water absorption of the treated RCA for the tested scenarios since the correlation coefficient between the percentage of cement been replaced by RHA and the water absorption of the treated RCA is 0.844 (≈1). According to Figure 4.18, it can be observed in most scenarios that the water absorption of the treated RCA increases as the percentage of cement been replaced by RHA is increased; this confirms the positive value of the Pearson correlation coefficient. But it needs to be noted out that at the initial stages the water absorption of the treated RCA reduces until it achieves a minimum value, when approximately 0-20% of cement is been replaced with RHA.

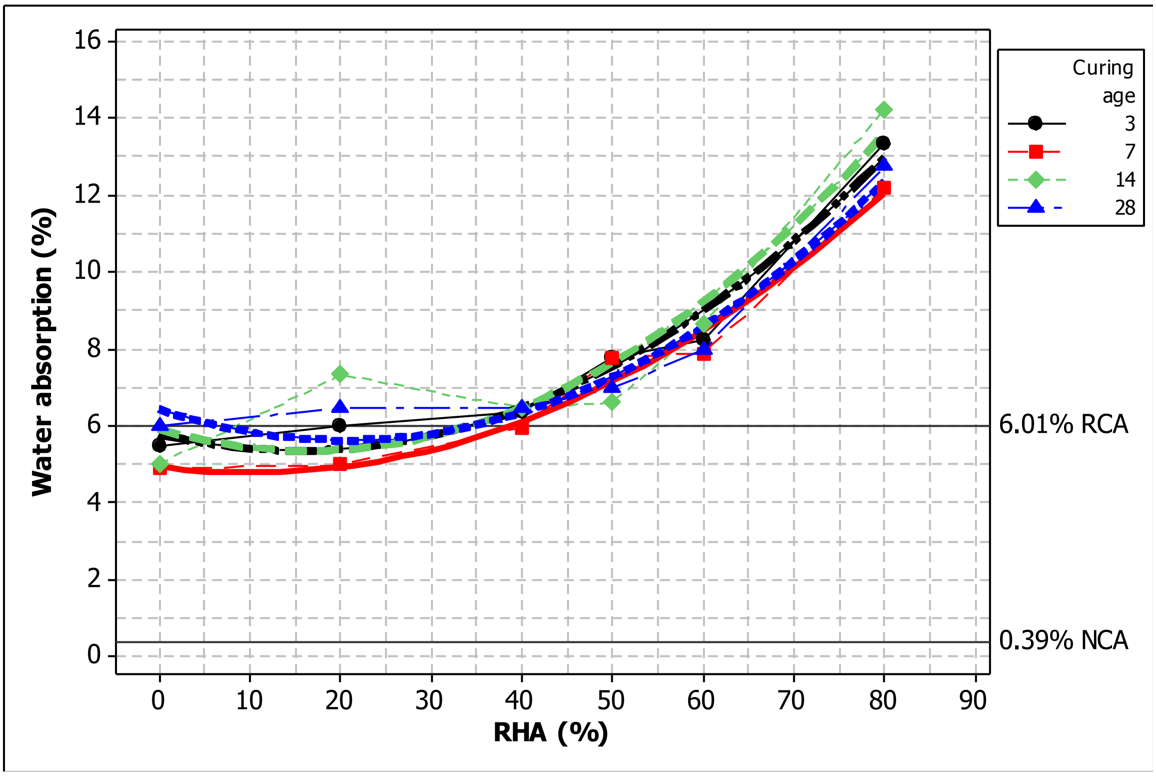


Figure 4. 18: Water Absorption of Treated RCA treated with Slurry (Liquid: Solid) Ratio of 0.625 for Varying RHA: Cement Ratios at Varying Curing Ages

By analyzing Table 4.32, it can be seen that the maximum reduction in the water absorption of RCA can be achieved when approximately 10-20% of cement is been replaced with RHA. This indicates that there is an effect on the water absorption of the RCA when it's been treated with a slurry that contains both RHA and cement. But beyond 30-40% of replacement of cement with RHA will cause the water absorption of the treated RCA to increase beyond the water absorption of untreated RCA (= 6.01%). It is mainly due to the lack of cement in the slurry that will trigger the pozzolanic reaction of the excess RHA. Since a very thick slurry of 0.625 is used to treat the RCA shown in Figure 4.18, the effect the percentage of RHA present in the slurry to treat RCA has on the water absorption of the treated RCA may be high.

Table 4. 32: Best Fit Lines for the Plotted Data Shown in Figure 4.18

Curing Age (Days)	**Equation of Best Fit Line (Regression Fit) [Quadratic Equation]**	**R^2 (%)**	**Stationary Point (Coordinates)**	
			Minima	
			X	**Y**
3	[Water absorption (%)] = 5.803 - 0.05602 [RHA (%)] + 0.001827 [RHA (%)]^2	97.1	15.33	5.37
7	[Water absorption (%)] = 4.951 - 0.02985 [RHA (%)] + 0.001487 [RHA (%)]^2	97.9	10.04	4.80
14	[Water absorption (%)] = 5.930 - 0.06755 [RHA (%)] + 0.002048 [RHA (%)]^2	87.8	16.49	5.37
28	[Water absorption (%)] = 6.448 - 0.07834 [RHA (%)] + 0.001907 [RHA (%)]^2	95.4	20.54	5.64

The correlation coefficient between the age of curing and the water absorption of the treated RCA is 0.020 having a P-value of 0.917. It can't be confirmed with a 90% confidence that the correlation coefficient between the age of curing and the water absorption of the treated RCA is significantly different from zero since the P-value is 0.917 (>0.10). The best fit curves presented in the Figure 4.18, that represents the water absorption of the treated RCA for a given curing age also do not show a large variation with one another. This may indicate that when cement present in the slurry is been replaced with RHA the water absorption of the treated RCA is not strongly correlated with the age of curing. But it can be stated that there is a very small positive correlation (= 0.020) between the age of curing and the water absorption of the treated RCA for the tested scenarios.

According to Table 4.32, the minimum water absorption (=4.80%) was obtained at a curing age of 7 days. When observing Figure 4.18, it can be distinctively seen in all the cases been tested that the water absorption is lowest at a curing age of 7 days than any other curing age been tested. Furthermore the water absorption of the treated RCA obtained at a curing age of 3 and 14 days in most of the scenarios analyzed are greater than that obtained at a curing age of 7 days. Similar behavioral patterns were observed in the water absorption of the treated RCA for all slurry ratios been used to coat RCA. Therefore when RCA is treated with slurry (Liquid: Solid) ratio of 0.625 for varying RHA: Cement ratios its best not to cure the treated RCA beyond 7 days in order to achieve the maximum reduction in its water absorption.

Table 4. 33: Water Absorption of Treated RCA Treated With Slurry (Liquid: Solid) Ratio of 0.625 for Varying RHA: Cement Ratios at Varying Curing Ages

Water Absorption of Treated RCA (%) [Mean ± SE]						
Curing Age (Days)	**RHA: Cement (%:%)**					
	0: 100	**20: 80**	**40: 60**	**50: 50**	**60: 40**	**80: 20**
3	5.51± 0.15	6.00± 0.19	6.40± 0.13	7.80± 0.09	8.26± 0.28	13.34± 0.35
7	4.91± 0.16	5.00± 0.12	5.98± 0.25	7.78± 0.76	7.91± 0.28	12.22± 0.93
14	5.03± 0.16	7.35± 0.81	6.48± 0.10	6.62± 0.07	8.65± 0.05	14.27± 0.70
28	6.04± 0.59	6.47± 0.02	6.49± 0.19	7.00± 0.72	8.01± 0.36	12.77± 0.25

The correlation coefficient between the percentage of cement been replaced by RHA and the water absorption of the treated RCA is 0.740 having a P-value of 0.000. It can be confirmed with a 95% confidence that the correlation coefficient between the percentage of cement been replaced by RHA and the water absorption of the treated RCA is significantly different from zero since the P-value is 0.000 (<0.05). Furthermore it can be stated that there is a strong positive correlation between the percentage of cement been replaced by RHA and the water absorption of the treated RCA for the tested scenarios since the correlation coefficient between the percentage of cement been replaced by RHA and the water absorption of the treated RCA is 0.740 (≈ 1). According to Figure 4.19, it can be observed in most scenarios that the water absorption of the treated RCA increases as the percentage of cement been replaced by RHA is increased; this confirms the positive value of the Pearson correlation coefficient.

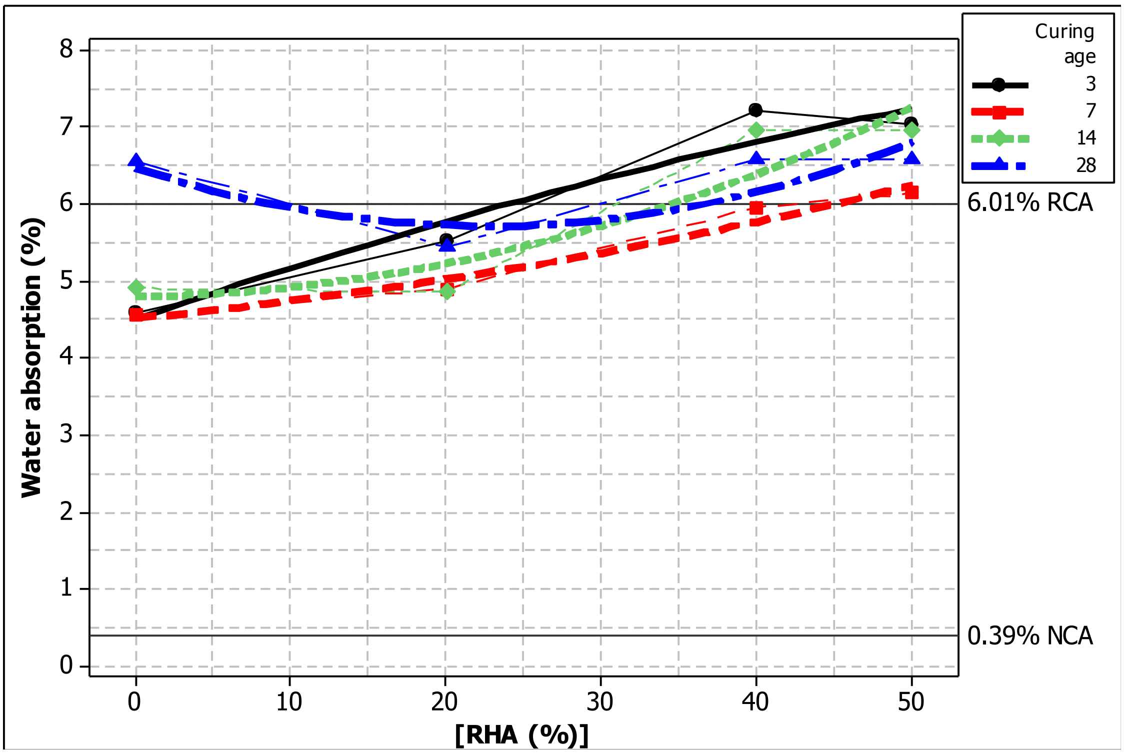


Figure 4. 19: Water Absorption of Treated RCA treated with Slurry (Liquid: Solid) Ratio of 0.75 for Varying RHA: Cement Ratios at Varying Curing Ages

By analyzing Table 4.34, it can be seen that the maximum reduction in the water absorption of RCA can be achieved when approximately 0-10% of cement is been replaced with RHA. It cannot be clearly stated that there is an effect on the water absorption of the RCA when it's been treated with a slurry having a ratio of 0.75 which contains both RHA and cement. But it is evident that beyond 30-40% of replacement of cement with RHA will cause the water absorption of the treated RCA to increase beyond the water absorption of untreated RCA (= 6.01%). It is mainly due to the lack of cement in the slurry that will trigger the pozzolanic reaction of the excess RHA. It needs to be pointed out that when the slurry been used to coat RCA gets thinner from 0.625 to 0.75, the water absorption of the RCA can be reduced even with a higher amount of cement been replaced with RHA. When the slurry been used to coat RCA gets thinner from 0.625 to 0.75 the correlation coefficient between the percentage of cement been replaced by RHA and the water absorption of the treated RCA reduces from 0.844 to 0.740. This indicates that the effect the percentage of RHA present in the slurry to treat RCA has on the water absorption of the treated RCA reduces when the slurry gets thinner.

Table 4. 34: Best Fit Lines for the Plotted Data Shown in Figure 4. 19

Curing Age (Days)	**Equation of Best Fit Line (Regression Fit) [Quadratic Equation]**	**R^2 (%)**	**Stationary Point (Coordinates)**	
			X	**Y**
3	[Water absorption (%)] = 4.497 + 0.06958 [RHA (%)] - 0.000298 [RHA (%)]^2	94.2	116.74	8.56
7	[Water absorption (%)] = 4.515 + 0.01867 [RHA (%)] + 0.000314 [RHA (%)]^2	96.5	-29.73	4.24
14	[Water absorption (%)] = 4.787 + 0.00343 [RHA (%)] + 0.000914 [RHA (%)]^2	87.1	-1.88	4.78
28	[Water absorption (%)] = 6.458 - 0.06626 [RHA (%)] + 0.001461 [RHA (%)]^2	66.5	22.68	5.71

The correlation coefficient between the age of curing and the water absorption of the treated RCA is 0.049 having a P-value of 0.847. It can't be confirmed with a 90% confidence that the correlation coefficient between the age of curing and the water absorption of the treated RCA is significantly different from zero since the P-value is 0.847 (>0.10). The best fit curves presented in the Figure 4.19, that represents the water absorption of the treated RCA for a given curing age also do not show a large variation with one another. This may indicate that when cement present in the slurry is been replaced with RHA the water absorption of the treated RCA is not strongly correlated with the age of curing. But it can be stated that there is a very small positive correlation between the age of curing and the water absorption of the treated RCA for the tested scenarios.

According to Table 4.34, the minimum water absorption (=4.24%) was obtained at a curing age of 7 days. When observing Figure 4.19, it can be distinctively seen in all the cases been tested that the water absorption is lowest at a curing age of 7 days than any other curing age been tested. Furthermore the water absorption of the treated RCA obtained at a curing age of 3 and 14 days in most of the scenarios analyzed are greater than that obtained at a curing age of 7 days. Similar behavioral patterns were observed in the water absorption of the treated RCA for all slurry ratios been used to coat RCA. Therefore when RCA is treated with slurry (Liquid: Solid) ratio of 0.75 for varying RHA: Cement ratios its best not to cure the treated RCA beyond 7 days in order to achieve the maximum reduction in its water absorption.

Table 4. 35: Water Absorption of Treated RCA Treated With Slurry (Liquid: Solid) Ratio of 0.75 for Varying RHA: Cement Ratios at Varying Curing Ages

Water Absorption of Treated RCA (%) [Mean ± SE]				
Curing Age (Days)	**RHA: Cement (%:%)**			
	0: 100	**20: 80**	**40: 60**	**50: 50**
3	4.58± 0.15	4.76± 0.23	4.97± 0.19	7.02± 0.12
7	4.55± 0.36	4.40± 0.01	5.95± 0.10	6.13± 0.16
14	4.90± 0.17	4.71± 0.29	5.07± 0.04	6.94± 0.05
28	6.54± 0.15	4.72± 0.32	5.48± 0.14	6.57± 0.07

The correlation coefficient between the percentage of cement been replaced by RHA and the water absorption of the treated RCA is -0.110 having a P-value of 0.664. It cannot be confirmed with a 90% confidence that the correlation coefficient between the percentage of cement been replaced by RHA and the water absorption of the treated RCA is significantly different from zero since the P-value is 0.664 (>0.10).

Furthermore it can be stated that there is a negative correlation between the percentage of cement been replaced by RHA and the water absorption of the treated RCA for the tested scenarios since the correlation coefficient between the percentage of cement been replaced by RHA and the water absorption of the treated RCA is -0.110. According to Figure 4.20, it can be observed in most scenarios that the water absorption of the treated RCA reduces as the percentage of cement been replaced by RHA is increased up to 25% and afterwards the water absorption of the treated RCA increases as the percentage of cement been replaced by RHA is increased beyond 25%.

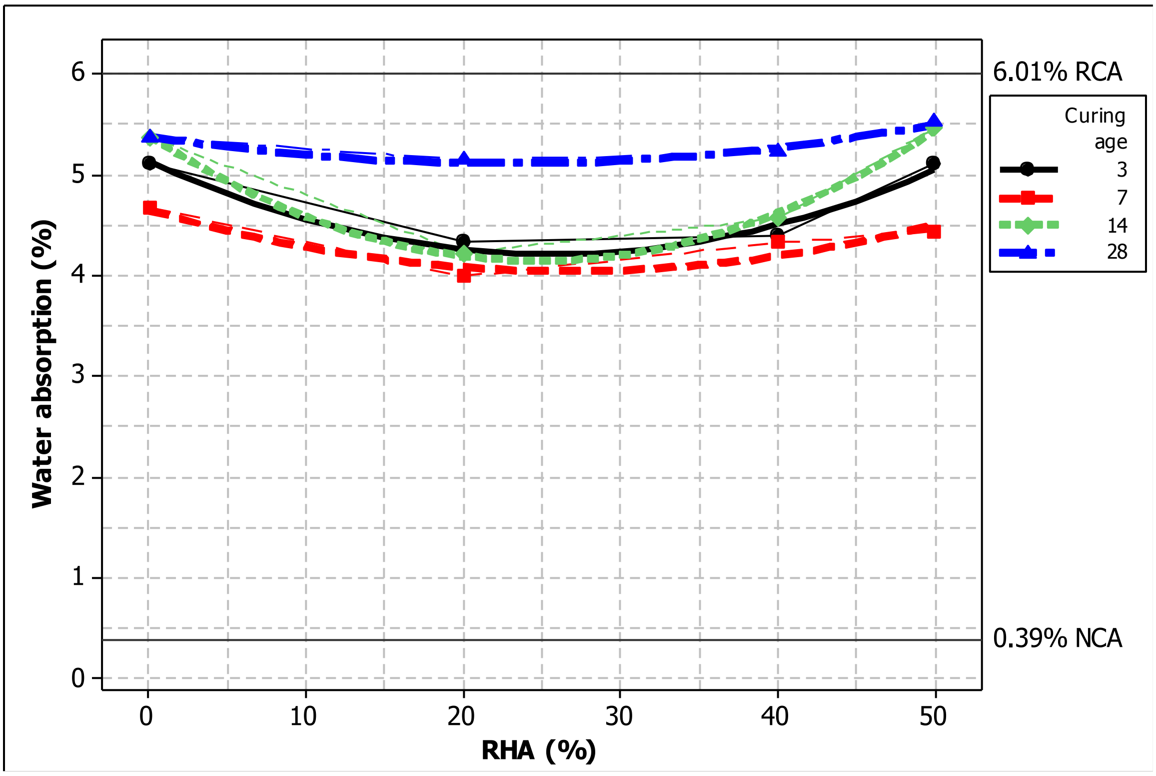


Figure 4. 20: Water Absorption of Treated RCA treated with Slurry (Liquid: Solid) Ratio of 0.875 for Varying RHA: Cement Ratios at Varying Curing Ages

By analyzing Table 4.36, it can be seen that the maximum reduction in the water absorption of RCA can be achieved when approximately 20-30% of cement is been replaced with RHA. It cannot be clearly stated that there is an effect on the water absorption of the RCA when it’s been treated with a slurry having a ratio of 0.875 which contains both RHA and cement. It is mainly due to the lack of cement in the slurry that will trigger the pozzolanic reaction of the excess RHA. It needs to be pointed out that when the slurry been used to coat RCA gets thinner from 0.625 to 0.75 to 0.875, the water absorption of the RCA can be reduced even with a higher amount of cement been replaced with RHA. When the slurry been used to coat RCA gets thinner from 0.625 to 0.75 to 0.875 the correlation coefficient between the percentage of cement been replaced by RHA and the water absorption of the treated RCA reduces from 0.844 to 0.740 to -0.110 respectively. This indicates that the effect the percentage of RHA present in the slurry to treat RCA has on the water absorption of the treated RCA reduces when the slurry gets thinner. Even when 40-50% of cement is replaced with RHA the water absorption of the treated RCA will not increase beyond the water absorption of untreated RCA (= 6.01%).

Table 4. 36: Best Fit Lines for the Plotted Data Shown in Figure 4.20

Curing Age (Days)	**Equation of Best Fit Line (Regression Fit) [Quadratic Equation]**	**R^2 (%)**	**Stationary Point (Coordinates)**	
			Minima	
			X	**Y**
3	[Water absorption (%)] = 5.138 - 0.07179 [RHA (%)] + 0.001402 $[\text{RHA (\%)}]^2$	96.1	25.60	4.22
7	[Water absorption (%)] = 4.656 - 0.04582 [RHA (%)] + 0.000858 $[\text{RHA (\%)}]^2$	87.0	26.70	4.04
14	[Water absorption (%)] = 5.388 - 0.1002 [RHA (%)] + 0.002025 $[\text{RHA (\%)}]^2$	99.6	24.74	4.15
28	[Water absorption (%)] = 5.385 - 0.02367 [RHA (%)] + 0.000522 $[\text{RHA (\%)}]^2$	96.2	22.67	5.12

The correlation coefficient between the age of curing and the water absorption of the treated RCA is 0.548 having a P-value of 0.019. It can be confirmed with a 95% confidence that the correlation coefficient between the age of curing and the water absorption of the treated RCA is significantly different from zero since the P-value is 0.019 (<0.05). The best fit curves presented in the Figure 4.20, that represents the water absorption of the treated RCA for a given curing age show a significant variation with one another. This may indicate that when cement present in thin slurries such as 0.875, is been replaced with RHA the water absorption of the treated RCA is strongly correlated with the age of curing. It can be stated that there is a positive correlation between the age of curing and the water absorption of the treated RCA for the tested scenarios.

According to Table 4.36, the minimum water absorption (=4.04%) was obtained at a curing age of 7 days. When observing Figure 4.20, it can be distinctively seen in all the cases been tested that the water absorption is lowest at a curing age of 7 days than any other curing age been tested. Furthermore the water absorption of the treated RCA obtained at a curing age of 3 and 14 days in most of the scenarios analyzed are greater than that obtained at a curing age of 7 days. Similar behavioral patterns were observed in the water absorption of the treated RCA for all slurry ratios been used to coat RCA. Therefore when RCA is treated with slurry (Liquid: Solid) ratio of 0.875 for varying RHA: Cement ratios its best not to cure the treated RCA beyond 7 days in order to achieve the maximum reduction in its water absorption.

Table 4. 37: Water Absorption of Treated RCA Treated With Slurry (Liquid: Solid) Ratio of 0.875 for Varying RHA: Cement Ratios at Varying Curing Ages

Water Absorption of Treated RCA (%) [Mean ± SE]				
Curing Age (Days)	**RHA: Cement (%:%)**			
	0: 100	**20: 80**	**40: 60**	**50: 50**
3	5.12± 0.16	4.34± 0.09	4.40± 0.00	5.11± 0.30
7	4.68± 0.05	3.99± 0.25	4.33± 0.01	4.44± 0.12
14	5.38± 0.10	4.23± 0.59	4.57± 0.01	5.47± 0.01
28	5.38± 0.11	5.15± 0.32	5.23± 0.01	5.53± 0.00

The correlation coefficient between the percentage of cement been replaced by RHA and the water absorption of the treated RCA is 0.501 having a P-value of 0.034. It can be confirmed with a 95% confidence that the correlation coefficient between the percentage of cement been replaced by RHA and the water absorption of the treated RCA is significantly different from zero since the P-value is 0.034 (<0.05). Furthermore it can be stated that there is a positive correlation between the percentage of cement been replaced by RHA and the water absorption of the treated RCA for the tested scenarios since the correlation coefficient between the percentage of cement been replaced by RHA and the water absorption of the treated RCA is 0.501. According to Figure 4.21, it can be observed in most scenarios that the water absorption of the treated RCA increases as the percentage of cement been replaced by RHA is increased; this confirms the positive value of the Pearson correlation coefficient.

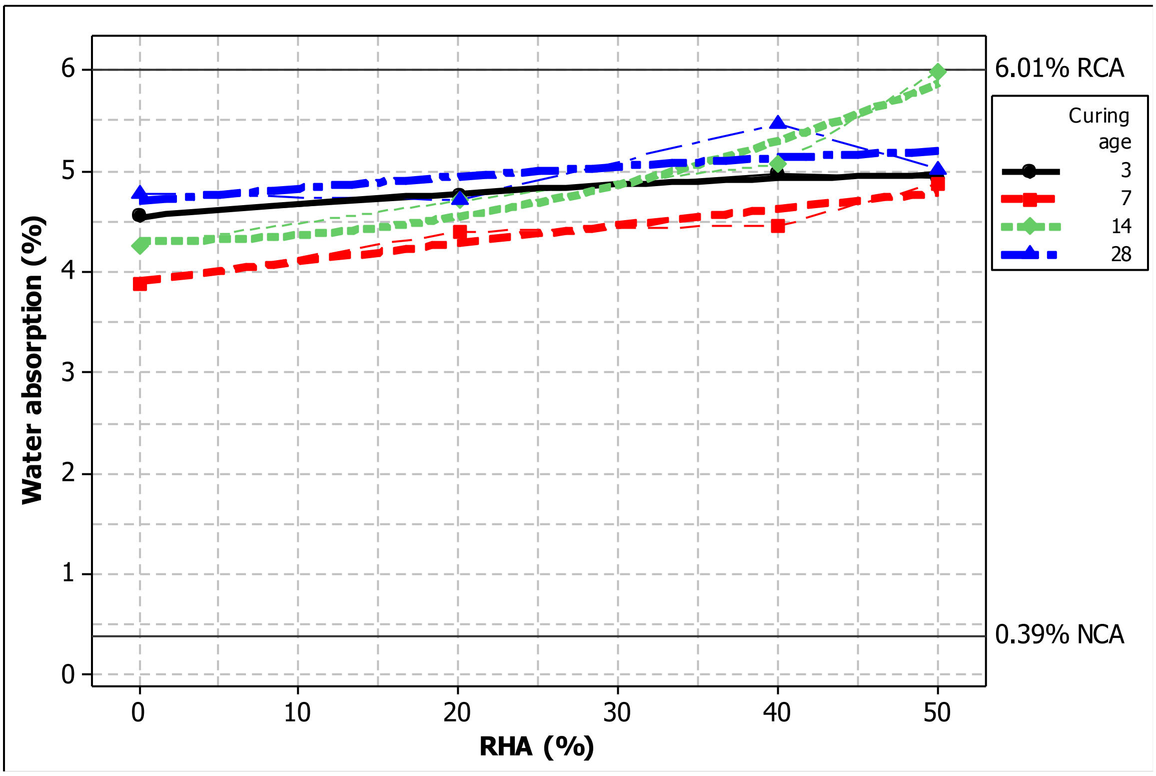


Figure 4. 21: Water Absorption of Treated RCA treated with Slurry (Liquid: Solid) Ratio of 1.00 for Varying RHA: Cement Ratios at Varying Curing Ages

By analyzing Table 4.38, it can be seen that the maximum reduction in the water absorption of RCA can be achieved when approximately 0-10% of cement is been replaced with RHA. It can be clearly seen that there is an effect in the water absorption of the RCA when it’s been treated with a slurry having a ratio of 1.00

which contains both RHA and cement. It needs to be pointed out that when the slurry been used to coat RCA gets thinner from 0.625 to 0.75 to 0.875 to 1.00, the water absorption of the RCA can be reduced even with a higher amount of cement been replaced with RHA. But when the slurry been used to coat RCA gets thinner from 0.625 to 0.75 to 0.875 to 1.00 the correlation coefficient between the percentage of cement been replaced by RHA and the water absorption of the treated RCA reduces until a slurry ratio of 0.875 and then increases rapidly when a slurry ratio of 1.00 is used, from 0.844 to 0.740 to -0.110 to 0.501 respectively. This indicates that the effect the percentage of RHA present in the slurry to treat RCA has on the water absorption of the treated RCA reduces when the slurry gets thinner and beyond a certain limit (=0.875) increases. But it should be highlighted that even when 40-50% of cement is replaced with RHA the water absorption of the treated RCA will not increase beyond the water absorption of untreated RCA (= 6.01%).

Table 4. 38: Best Fit Lines for the Plotted Data Shown in Figure 4.21

Curing Age (Days)	**Equation of Best Fit Line (Regression Fit) [Quadratic Equation]**	**R^2 (%)**	**Stationary Point (Coordinates)**	
			X	**Y**
3	[Water absorption (%)] = 4.547 + 0.01409 [RHA (%)] - 0.000114 [RHA (%)]^2	97.2	61.80	4.98
7	[Water absorption (%)] = 3.914 + 0.01972 [RHA (%)] - 0.000044 [RHA (%)]^2	90.2	224.09	6.12
14	[Water absorption (%)] = 4.311 - 0.00066 [RHA (%)] + 0.000638 [RHA (%)]^2	94.1	0.52	4.31
28	[Water absorption (%)] = 4.705 + 0.01389 [RHA (%)] - 0.000078 [RHA (%)]^2	41.7	89.04	5.32

The correlation coefficient between the age of curing and the water absorption of the treated RCA is 0.464 having a P-value of 0.053. It can be confirmed with a 94%

confidence that the correlation coefficient between the age of curing and the water absorption of the treated RCA is significantly different from zero since the P-value is 0.053 (<0.06). The best fit curves presented in the Figure 4.21, that represents the water absorption of the treated RCA for a given curing age show a significant variation with one another. This may indicate that when cement present in thin slurries such as 1.00, is been replaced with RHA the water absorption of the treated RCA is strongly correlated with the age of curing. A similar behavioral pattern was observed when the RCA was coated with a slurry having a liquid to solid composition of 0.875. It can be stated that there is a positive correlation between the age of curing and the water absorption of the treated RCA for the tested scenarios.

When observing Figure 4.21, it can be distinctively seen in all the cases been tested that the water absorption is lowest at a curing age of 7 days than any other curing age been tested. Furthermore the water absorption of the treated RCA obtained at a curing age of 3 and 14 days in most of the scenarios analyzed are greater than that obtained at a curing age of 7 days. Similar behavioral patterns were observed in the water absorption of the treated RCA for all slurry ratios been used to coat RCA. Therefore when RCA is treated with slurry (Liquid: Solid) ratio of 1.000 for varying RHA: Cement ratios its best not to cure the treated RCA beyond 7 days in order to achieve the maximum reduction in its water absorption.

Table 4. 39: Water Absorption of Treated RCA Treated With Slurry (Liquid: Solid) Ratio of 1.00 for Varying RHA: Cement Ratios at Varying Curing Ages

Water Absorption of Treated RCA (%) [Mean ± SE]				
Curing age (days)	**RHA: Cement (%:%)**			
	0: 100	**20: 80**	**40: 60**	**50: 50**
3	4.56± 0.38	4.76± 0.23	4.97± 0.19	4.94± 0.09
7	3.88± 0.13	4.40± 0.01	4.47± 0.01	4.88± 0.02
14	4.26± 0.21	4.71± 0.29	5.07± 0.04	6.00± 0.05
28	4.77± 0.00	4.72± 0.32	5.48± 0.14	5.02± 0.13

4.2.2.1.2. Specific Gravity

According to Figure 4.18 and Figure 4.22, it can be clearly seen that there is a strong negative correlation between the water absorption of the treated RCA and its relative density since the Pearson correlation of the water absorption of the treated RCA and its relative density (SSD basis) is -0.986 (≈1). Hence it can be clearly confirmed having a 95% confidence that the correlation coefficient between the water absorption of the treated RCA and its relative density is significantly different from zero since the P-Value is 0.000 (<0.05). Therefore it can be stated that the water absorption of the treated RCA and its relative density is inversely proportional.

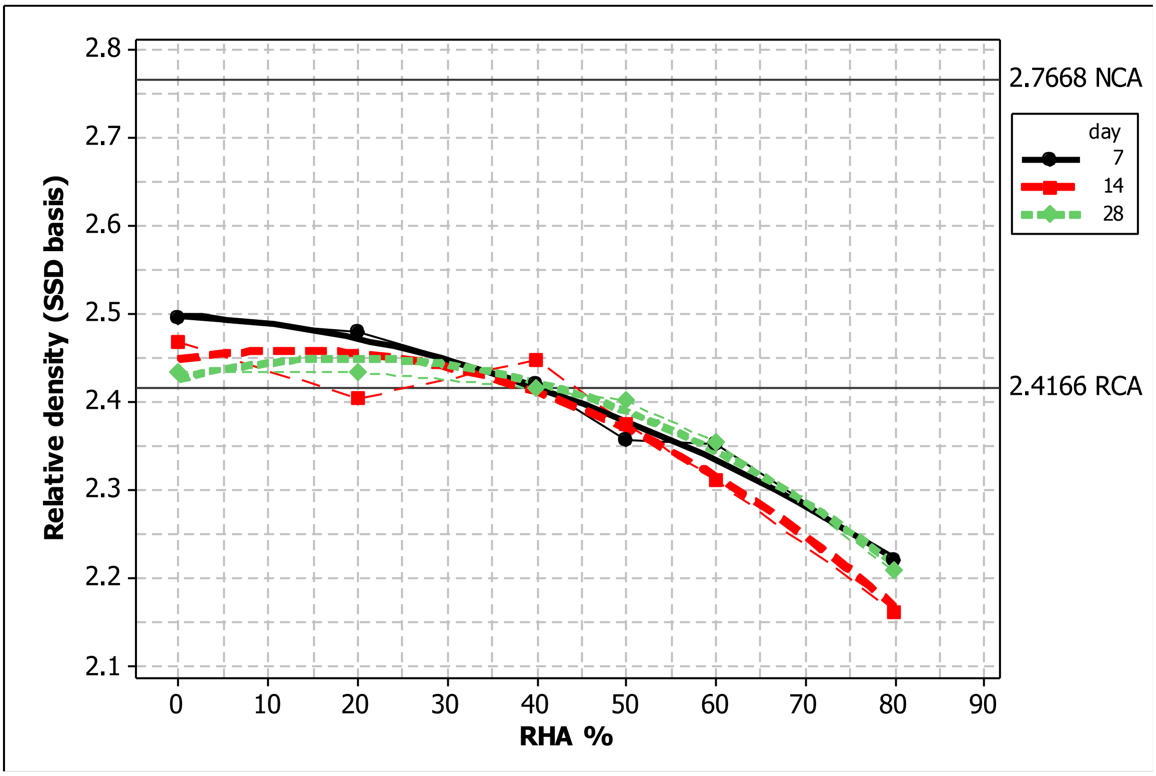


Figure 4. 22: Variation of Relative Density (on SSD basis) for a Fixed Slurry Ratio (Liquid: Solid) of 0.625 Containing Varying Proportions of RHA: Cement Percentages for Different Curing Ages

Table 4. 40: Best Fit Lines for the Plotted Data Shown in Figure 4. 22

Curing Age (Days)	**Equation of Best Fit Line (Regression Fit) [Quadratic Equation]**	**R^2 (%)**	**Stationary Point (Coordinates)**	
			X	**Y**
7	[Relative density (SSD basis)] = 2.500 - 0.000659 [RHA %] - 0.000035 [RHA %]^2	98.2	-9.41	2.50
14	[Relative density (SSD basis)] = 2.449 + 0.001665 [RHA %] - 0.000065 [RHA %]^2	93.0	12.81	2.46
28	[Relative density (SSD basis)] = 2.428 + 0.002419 [RHA %] - 0.000063 [RHA %]^2	98.3	19.20	2.45

Even though RCA was treated with RHA: cement slurry all the resultant TRCA’s are very much lighter than NCA since all the specific gravity values of TRCA’s are lower than that of NCA (= 2.7668).

Table 4. 41: Relative Density (on SSD Basis) of Treated RCA that had been Treated with Slurry (Liquid: Solid) Ratio of 0.625 for Varying RHA: Cement Ratios at Varying Curing Ages

Water Absorption of Treated RCA (%) [Mean ± SE]						
Curing Age (Days)	**RHA: Cement (%:%)**					
	0: 100	**20: 80**	**40: 60**	**50: 50**	**60: 40**	**80: 20**
7	2.50± 0.01	2.48± 0.02	2.42± 0.01	2.36± 0.02	2.35± 0.02	2.22± 0.00
14	2.47± 0.02	2.41± 0.03	2.45± 0.02	2.38± 0.01	2.31± 0.00	2.16± 0.01
28	2.44± 0.02	2.44± 0.00	2.42± 0.02	2.40± 0.02	2.36± 0.00	2.21± 0.01

4.2.2.2. Mortar Cube Strength of Each Slurry Scenario

The correlation coefficient between the percentage of cement been replaced by RHA and the strength of the mortar cubes made with the slurry is -0.889 having a P-value of 0.000. It can be confirmed with a 95% confidence that the correlation coefficient between the percentage of cement been replaced by RHA and the strength of the mortar cubes made with the slurry is significantly different from zero since the P-value is 0.000 (<0.05). Furthermore it can be stated that there is a strong negative correlation between the percentage of cement been replaced by RHA and the strength of the mortar cubes made with the slurry for the tested scenarios since the correlation coefficient between the percentage of cement been replaced by RHA and the strength of the mortar cubes made with the slurry is -0.889 (≈1). According to Figure 4.23, it can be clearly seen that the strength of the mortar cubes reduces as the percentage of cement been replaced by RHA is increased; this confirms the negative value of the Pearson correlation coefficient.

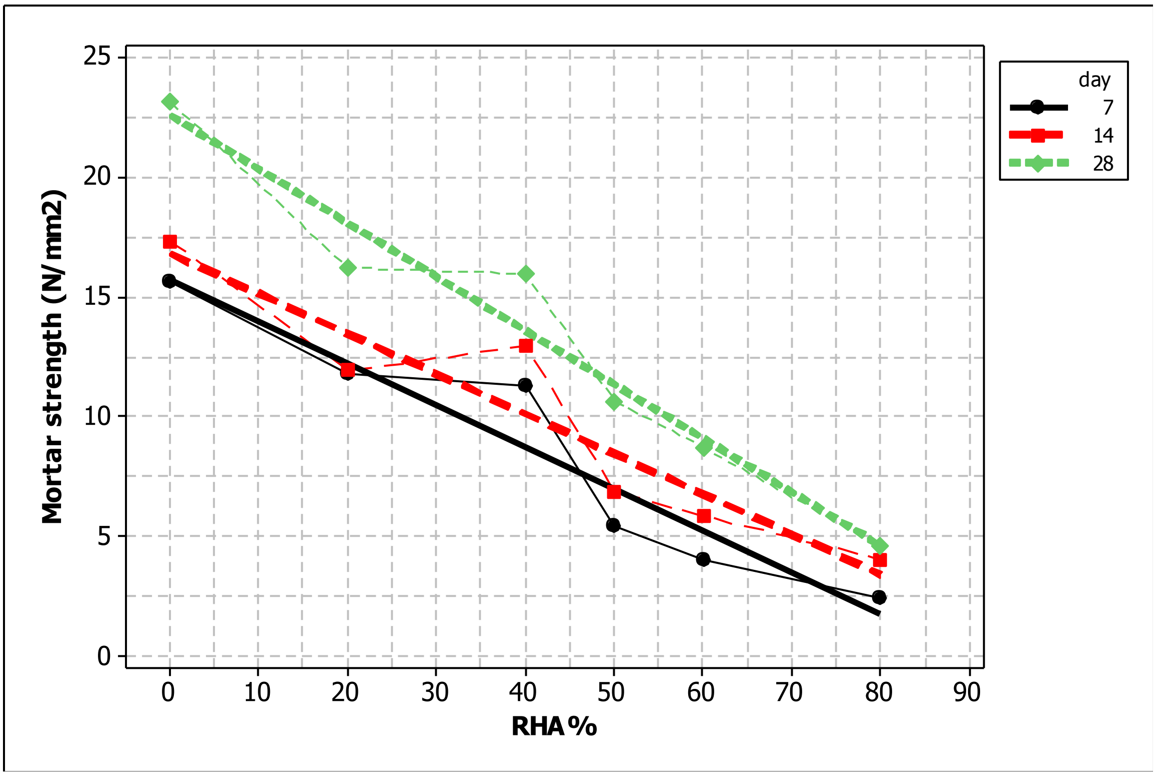


Figure 4. 23: Strength of Mortar Cubes at Different Curing Ages made with a Slurry Ratio (Liquid: Solid) of 0.625 by Varying the RHA (%) and Cement (%)

Table 4. 42: Best Fit Lines for the Plotted Data Shown in Figure 4.23

Curing Age (Days)	Equation of Best Fit Line (Regression Fit) [Linear Equation]	R^2 (%)
7	[Mortar strength (N/mm2)] = 15.69 - 0.1745 [RHA%]	91.9
14	[Mortar strength (N/mm2)] = 16.81 - 0.1675 [RHA%]	88.8
28	[Mortar strength (N/mm2)] = 22.59 - 0.2250 [RHA%]	95.3

The correlation coefficient between the age of curing and the strength of the mortar cubes made with the slurry is 0.362 having a P-value of 0.140. It can be confirmed with a 85% confidence that the correlation coefficient between the age of curing and the strength of the mortar cubes made with the slurry is significantly different from zero since the P-value is 0.140 (<0.15). Furthermore it can be stated that there is a positive correlation between the age of curing and the strength of the mortar cubes made with the slurry for the tested scenarios since the correlation coefficient between the age of curing and the strength of the mortar cubes made with the slurry is 0.362. When analyzing the data shown in Figure 4.23, it can be seen that the mortar strength increases with the increase in the age of curing, as per the usual norm of strength gain in concrete.

The mortar cubes made with the slurries containing 100% cement achieved the highest strength of 23.16 N/mm2 at a curing age of 28 days. A very small drop in the 28 day strength of the motor cubes was observed when the replacement level of cement with RHA was increased from 20% to 40% and from 50% to 60% they are respectively, 0.24 N/mm2 and 1.91 N/mm2. According to Figure 4.23 and Table 4.43, a very steep drop in the 28 day strength of 5.34 N/mm2 of the motor cubes was observed when the replacement level of cement with RHA was increased from 40% to 50%. Therefore it can be denoted that the variation in the strength gain due to the replacement of cement with RHA is somewhat minute, up to a replacement level of 40%. When the replacement level of cement with RHA exceeds 40% a steep strength drop can be noticed. It is mainly due to the pozzolanic reaction that takes place between the SiO_2 present in RHA and the $Ca(OH)_2$ released from the hydration reaction of cement. According to Mindess et al., the pozzolanic reaction between SiO_2 and $Ca(HO)_2$ has a molar ratio of 2: 3. Hence when the replacement level of cement with RHA was increased from 40% to 50% a steep drop in the 28 day strength of the motor cubes can be observed.

$3Ca(OH)_2 + 2SiO_2 + 5H_2O \rightarrow 3CaO \cdot 2SiO_2 \cdot 8H_2O \ldots$ (1) (Mindess et al, 2002)

Table 4. 43: Strength of Mortar Cubes at Different Curing Ages Made With A Slurry Ratio (Liquid: Solid) Of 0.625 by Varying the RHA (%) and Cement (%)

Mortar Strength (N/Mm2) [Mean ± SE]						
Curing Age (Days)	**RHA: Cement (%:%)**					
	0: 100	**20: 80**	**40: 60**	**50: 50**	**60: 40**	**80: 20**
7	15.60± 0.71	11.77± 0.23	11.28± 0.45	5.46± 0.23	3.99± 0.06	2.42± 0.06
14	17.35± 1.37	11.93± 0.60	12.95± 0.85	6.85± 0.04	5.85± 0.30	4.03± 0.03
28	23.16± 0.81	16.21± 0.51	15.97± 0.33	10.63± 0.41	8.72± 0.46	4.58± 0.17

It can be pointed out that there is a significant strength drop of 4.14 N/mm2 in the 28 day strength of the motor cubes when the replacement level of cement with RHA was increased from 60% to 80%. It is mainly due to the large amount of RHA and a small amount of cement been present in the slurry. Therefore there is a shortage of cement that is required to react with all the RHA present in the paste. Due to the high amount of RHA that remains in the cement paste the mortar cubes made with 80% of RHA cannot achieve a high strength at 28 days.

When treating RCA with a slurry that contains a mixture of RHA and cement it can be concluded that beyond 40% replacement of cement with RHA is not advisable, since the coating that forms around the surface of the RCA will be of a lower strength.

The correlation coefficient between the slurry ratio that consisted 100% of cement that was used to coat RCA and the strength of the mortar cubes made with the slurry is -0.899 having a P-value of 0.000. It can be confirmed with a 95% confidence that the correlation coefficient between the slurry ratio used to coat RCA and the strength of the mortar cubes made with the slurry is significantly different from zero since the P-value is 0.000 (<0.05). Furthermore it can be stated that there is a strong negative correlation between the slurry ratio used to coat RCA and the strength of the mortar cubes made with the slurry for the tested scenarios since the correlation coefficient between the slurry ratio used to coat RCA and the strength of the mortar cubes made with the slurry is -0.899 (≈1). According to Figure 4.24, it can be clearly seen that the strength of the mortar cubes reduces as the slurry ratio used to coat RCA increases; this confirms the negative value of the Pearson correlation coefficient.

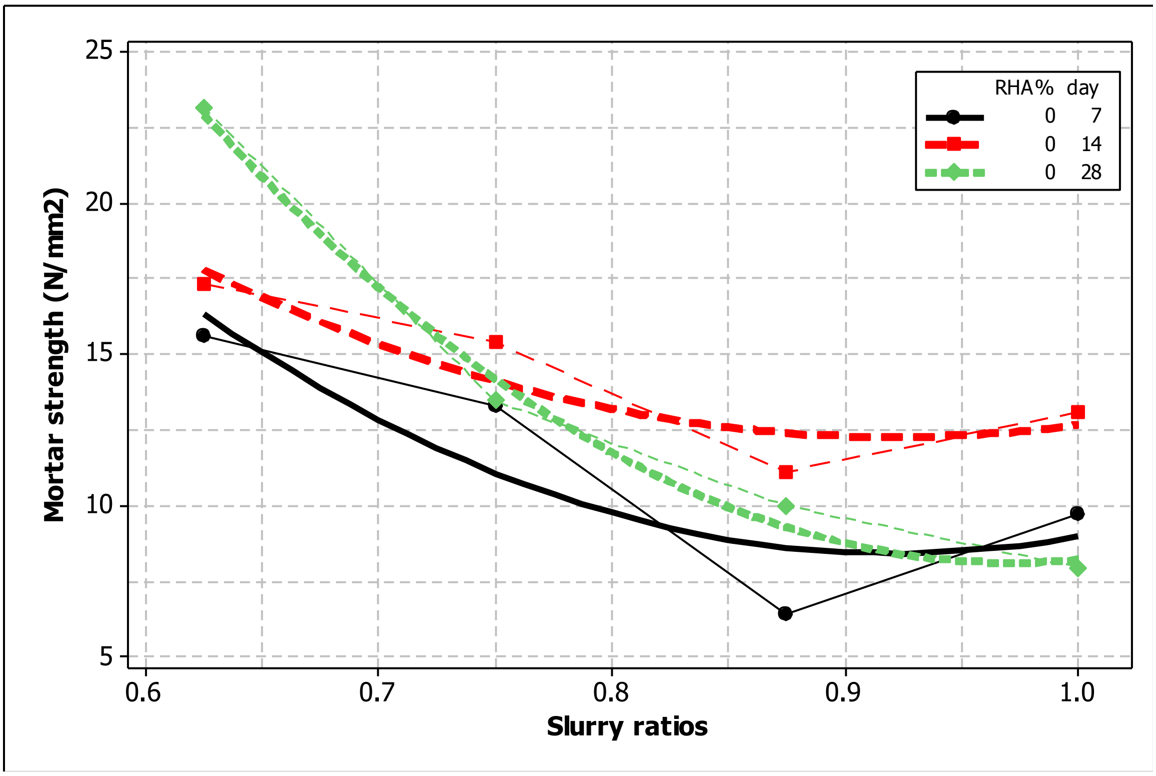


Figure 4. 24: Strength of Mortar Cubes at Different Curing Ages Made With Varying Slurry Ratios (Liquid: Solid) for a RHA (%): Cement (%) Content of 0 (%): 100 (%)

Table 4. 44: Best Fit Lines for the Plotted Data Shown in Figure 4. 24

Curing Age (Days)	**Equation of Best Fit Line (Regression Fit) [Quadratic Equation]**	**R^2 (%)**	**Stationary Point (Coordinates)**	
			X	**X**
7	[Mortar strength N/mm2)] = 85.13 - 166.6 [Slurry ratios] + 90.4 [Slurry ratios]^2	77.8	0.92	8.37
14	[Mortar strength N/mm2)] = 65.59 - 115.7 [Slurry ratios] + 62.78 [Slurry ratios]^2	83.4	0.92	12.28
28	[Mortar strength N/mm2)] = 124.2 - 238.7 [Slurry ratios] + 122.7 [Slurry ratios]^2	99.2	0.97	8.11

Table 4. 45: Strength of Mortar Cubes at Different Curing Ages Made With Varying Slurry Ratios (Liquid: Solid) for A RHA (%): Cement (%) Content Of 0 (%): 100 (%)

Mortar Strength (N/Mm2) [Mean ± SE]				
Age of Curing (Days)	**Slurry Ratio (Liquid: Solid)**			
	0.625	**0.75**	**0.875**	**1.000**
7	15.60± 0.71	13.27± 0.30	6.38± 0.46	9.70± 0.21
14	17.35± 1.37	15.39± 0.47	11.10± 0.58	13.07± 0.25
28	23.16± 0.81	13.46± 0.23	9.97± 0.37	7.94± 0.55

The correlation coefficient between the age of curing and the strength of the mortar cubes made with the slurry is 0.178 having a P-value of 0.580. It cannot be confirmed with even a 85% confidence that the correlation coefficient between the age of curing and the strength of the mortar cubes made with the slurry is significantly different from zero since the P-value is 0.580 (>0.15). but it can be stated that there is a positive correlation between the age of curing and the strength of the mortar cubes made with the slurry for the tested scenarios since the correlation coefficient between the age of curing and the strength of the mortar cubes made with the slurry is 0.178. When analyzing the data shown in Figure 4.24, it can be seen in all slurry ratios the mortar strength increases from an age of curing of 7 days to 14 days, but when the slurry ratio used to prepare the mortar cubes are thinner than 0.625 (i.e. 0.75, 0.875 and 1.000) the mortar strength reduces from an age of curing of 14 days to 28 days.

The correlation coefficient between the slurry ratio that consisted 20% of RHA and 80% of cement that was used to coat RCA and the strength of the mortar cubes made with the slurry is -0.703 having a P-value of 0.011. It can be confirmed with a 95% confidence that the correlation coefficient between the slurry ratio used to coat RCA and the strength of the mortar cubes made with the slurry is significantly different from zero since the P-value is 0.011 (<0.05). Furthermore it can be stated that there is a strong negative correlation between the slurry ratio used to coat RCA and the strength of the mortar cubes made with the slurry for the tested scenarios since the correlation coefficient between the slurry ratio used to coat RCA and the strength of the mortar cubes made with the slurry is -0.703 (≈1). According to Figure 4.25, it can be clearly seen that the strength of the mortar cubes reduces as the slurry ratio used to coat RCA increases; this confirms the negative value of the Pearson correlation coefficient.

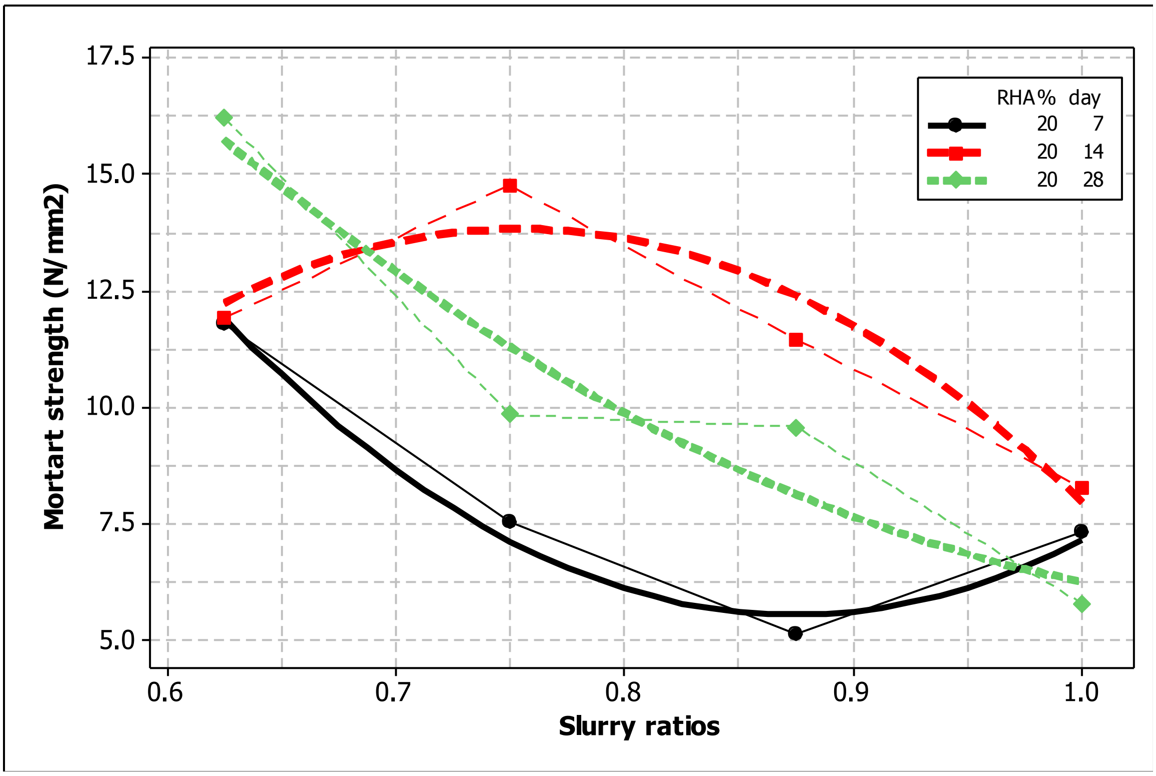


Figure 4. 25: Strength of Mortar Cubes at Different Curing Ages made with Varying Slurry Ratios (Liquid: Solid) for a RHA (%): Cement (%) Content of 20 (%): 80 (%)

Table 4. 46: Best Fit Lines for the Plotted Data Shown in Figure 4. 25

Curing Age (Days)	**Equation of Best Fit Line (Regression Fit) [Quadratic Equation]**	**R^2 (%)**	**Stationary Point (Coordinates)**	
			X	**Y**
7	[Mortar strength N/mm2)] = 84.12 - 179.8 [Slurry ratios] + 102.8 [Slurry ratios]^2	98.2	0.875	5.501
14	[Mortar strength N/mm2)] = - 40.96 + 145.5 [Slurry ratios] - 96.60 [Slurry ratios]^2	90.8	0.753	13.828
28	[Mortar strength N/mm2)] = 57.23 - 92.1 [Slurry ratios] + 41.10 [Slurry ratios]^2	91.7	1.120	5.634

Table 4. 47: Strength of Mortar Cubes at Different Curing Ages Made With Varying Slurry Ratios (Liquid: Solid) for A RHA (%): Cement (%) Content of 20 (%): 80 (%)

Mortar Strength (N/Mm2) [Mean ± SE]				
Age of Curing (Days)	**Slurry Ratio (Liquid: Solid)**			
	0.625	**0.75**	**0.875**	**1.000**
7	11.77± 0.23	7.55± 0.14	5.10± 0.23	7.30± 0.35
14	11.93± 0.60	14.76± 0.51	11.45± 0.13	8.25± 0.36
28	16.21± 0.51	9.83± 0.55	9.57± 0.76	5.76± 0.40

The correlation coefficient between the age of curing and the strength of the mortar cubes made with the slurry is 0.228 having a P-value of 0.475. It cannot be confirmed with even a 85% confidence that the correlation coefficient between the age of curing and the strength of the mortar cubes made with the slurry is significantly different from zero since the P-value is 0.475 (>0.15). But it can be stated that there is a positive correlation between the age of curing and the strength of the mortar cubes made with the slurry for the tested scenarios since the correlation coefficient between the age of curing and the strength of the mortar cubes made with the slurry is 0.228. When analyzing the data shown in Figure 4.25, it can be seen in all slurry ratios the mortar strength increases from an age of curing of 7 days to 14 days, but when the slurry ratio used to prepare the mortar cubes are thinner than 0.625 (i.e. 0.75, 0.875 and 1.000) the mortar strength reduces from an age of curing of 14 days to 28 days. A similar behavior was analyzed when various slurry ratios containing 100% of cement was used to make the mortar cubes as seen in Figure 4.24.

When the thickness of the slurry reduces the amount of water present in the cement-RHA paste increases, therefore the amount of cement or cement-RHA present in the paste is insufficient to chemically react with the comparatively large amount of water present in the paste. Therefore a lot of free water will be left in the mortar cubes which with time will lead to the formation of large pores in the mortar cubes. Due to the hydration reaction and pozzolanic reaction the mortar cube strength increases when the age of curing increases from 7 days to 14 days. When thin slurries were used, after an age of curing of 14 days there was no strength gain but a strength drop, this is mainly due to the formation of large pores in the mortar cubes by the excess water.

Therefore it can be seen that when the slurry gets thinner the strength of the coating reduces but as mentioned in the previous sections as the slurry gets thinner the ability of the RHA- cement mixture to get impregnated in to the pores and micro cracks present on the surface of the RCA increases. When slurry ratios having the ranges of 1.5-1.6 or 0.85-1.05 depending on the percentage of cement and RHA present in the slurry are used to coat RCA, the C-S-H binder produced by the hydration reaction and the pozzolanic reaction will get deposited in the pores and micro fissures on the surface of RCA thereby strengthening the weak surface of RCA. But if the slurry ratios used to coat RCA is either thicker or thinner than the given ranges the C-S-H binder will not get deposited in the pores and micro fissures present on the surface of RCA hence furthermore reducing the physical properties of RCA. If RCA was treated with a slurry that is thinner than the specified range then the coating around the RCA will be weak therefore this will contribute to a very weak interfacial transition zone when concrete is made with such TRCA’s, hence reducing the strength of the concrete.

4.2.3. Selecting the Best Surface Treatment Method

4.2.3.1. Comparison of the Water Absorption Test Results Obtained After Treating It with the Ground Rice Husk Ash (RHA) - Lime Slurry and the Ground Rice Husk Ash (RHA) - Cement Slurry

When analyzing the water absorption values of the RCA that were coated with RHA-cement slurries, it was very clear that the maximum reduction in water absorption of RCA was achieved at a curing age of 7 days. Hence in this section when RCA is coated with RHA-cement slurries the water absorption values of TRCA will only be considered at a curing age of 7 days since it was where the optimum reduction was obtained.

The water absorption values of TRCA's that were treated with RHA-lime slurries and cured for 24 hours and the water absorption values of TRCA's that were treated with RHA-cement slurries and cured for 7 days are given in Table 4.48 and are graphically presented in Figure 4.26. According to Table 4.48 and Figure 4.26, it is evident that in all scenarios the water absorption values of TRCA's that were treated with RHA-lime slurries and cured for 24 hours are greater than the water absorption values of TRCA's that were treated with RHA-cement slurries and cured for 7 days. Therefore it can be stated that RHA-cement slurry is much better than RHA-lime slurry to treat RCA.

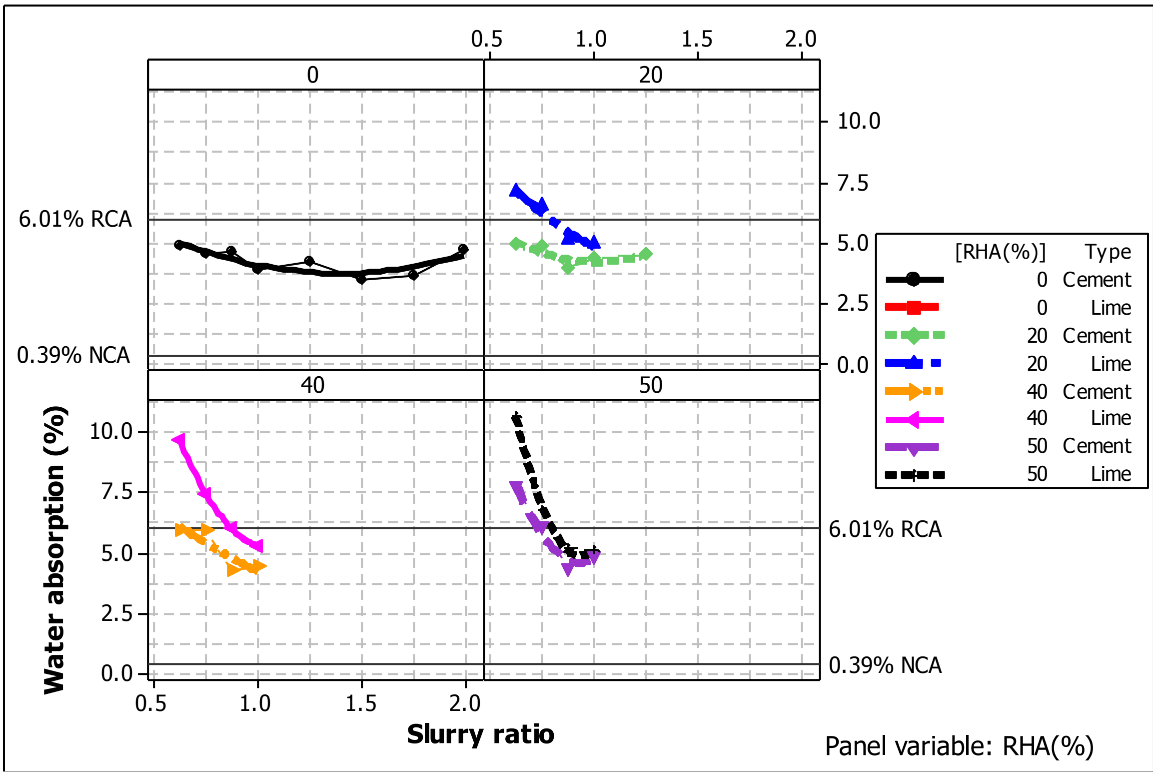


Figure 4. 26: The Water Absorption of TRCA's that had achieved the Maximum Reduction when been treated with the Ground Rice Husk Ash (RHA) - Lime Slurry and the Ground Rice Husk Ash (RHA) - Cement Slurry

According to Figure 4.27 and Table 4.48, the maximum reduction in the water absorption values of TRCA's that were treated with slurries that contained 100% of cement were obtained at the slurry ratios that were between 1.5-1.6 and the maximum reduction in the water absorption values of TRCA's that were treated with slurries that contained a mixture of RHA and cement were achieved at the slurry ratios that were between 0.85-1.05. Hence the scenarios shown in Table 4.49 were selected to treat the RCA in order to make the concrete specimens.

Table 4. 48: The Water Absorption of TRCA's That Had Achieved the Maximum Reduction When Been treated with the Ground Rice Husk Ash (RHA) - Lime Slurry and the Ground Rice Husk Ash (RHA) - Cement Slurry

Water Absorption of Treated RCA (%) [Mean ± SE]										
RHA (%)			**Slurry Ratio (Liquid: Solid)**							
			0.625	**0.75**	**0.875**	**1.00**	**1.25**	**1.50**	**1.75**	**2.00**
0	**100**	**Cement (%)**	4.91± 0.16	4.55± 0.36	4.68± 0.05	3.88± 0.13	4.29± 0.01	3.53± 0.09	3.68± 0.05	4.78± 0.58
		Lime (%)	-	-	-	-	-	-	-	-
20	**80**	**Cement (%)**	5.00± 0.12	4.89± 0.09	3.99± 0.25	4.40± 0.01	-	-	-	-
		Lime (%)	7.11± 0.57	6.58± 0.43	5.17± 0.33	4.98± 0.41	-	-	-	-
40	**60**	**Cement (%)**	5.98± 0.25	5.95± 0.10	4.33± 0.01	4.47± 0.01	-	-	-	-
		Lime (%)	9.73± 0.00	7.49± 0.58	6.07± 0.00	5.32± 0.32	-	-	-	-
50	**50**	**Cement (%)**	7.78± 0.76	6.13± 0.16	4.44± 0.12	4.88± 0.02	-	-	-	-
		Lime (%)	10.74± 0.81	6.84± 0.01	5.27± 0.53	5.12± 0.36	-	-	-	-

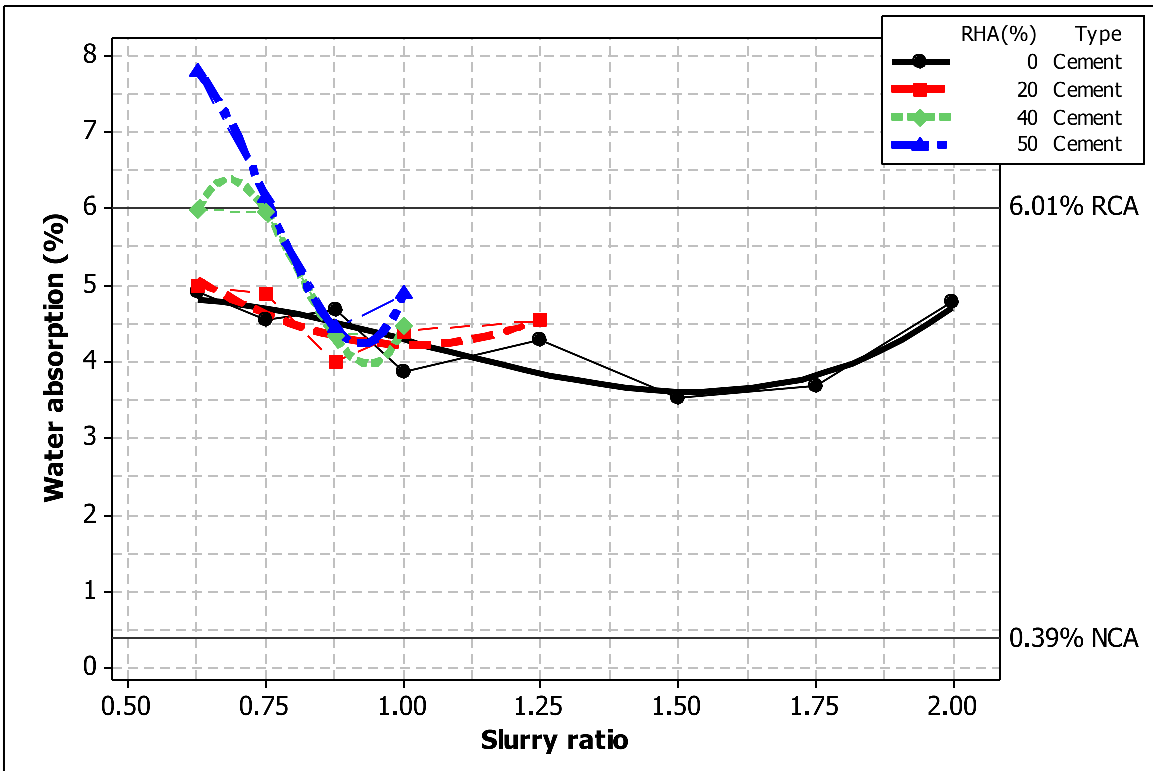


Figure 4. 27: The Water Absorption Values of TRCA's that were treated with RHA-Cement Slurries and Cured for 7 days

Table 4. 49: Scenarios of Coarse Aggregates That Had Been Used to Make the Concrete Specimens

Type of Coarse Aggregate	Slurry Ratio (Liquid: Solid)	RHA: Cement (%:%)
TRCA 1	1.500	0%: 100%
TRCA 2	0.875	20%: 80%
TRCA 3		40%: 60%

4.2.3.2. Comparison of the Mortar Cube Strength Results Obtained From the Ground Rice Husk Ash (RHA) - Lime Slurry and the Ground Rice Husk Ash (RHA) - Cement Slurry

The strength of the mortar cubes made with a specific slurry can be used to predict the strength of the coating around the surface of RCA that had been treated with that specific slurry. According to Figure 4.28 and Table 4.50, it can be clearly seen that the RHA-cement slurry is much stronger than the RHA-lime slurry. Even during testing it was noticed that when the air dried TRCA's that had been coated with RHA-lime slurries had been placed in water for curing purposes or during testing or after oven drying the TRCA's a large amount of the coating around the surface of the RCA got dissolved in the water or remained on surface of the cloth used to wipe the TRCA's during the water absorption test or remained in the plates as a dust after oven drying the TRCA's as shown in Figure 4.29 and Figure 4.30. These drawbacks were not noticed while testing the TRCA's that were coated with RHA-cement slurries. If TRCA's coated with RHA-lime slurry is used to produce structural concrete it would cause a lot of detrimental impacts on the performance of concrete due to the weak RHA-lime coating around its surface. Hence it is best to treat RCA with RHA-cement slurry.

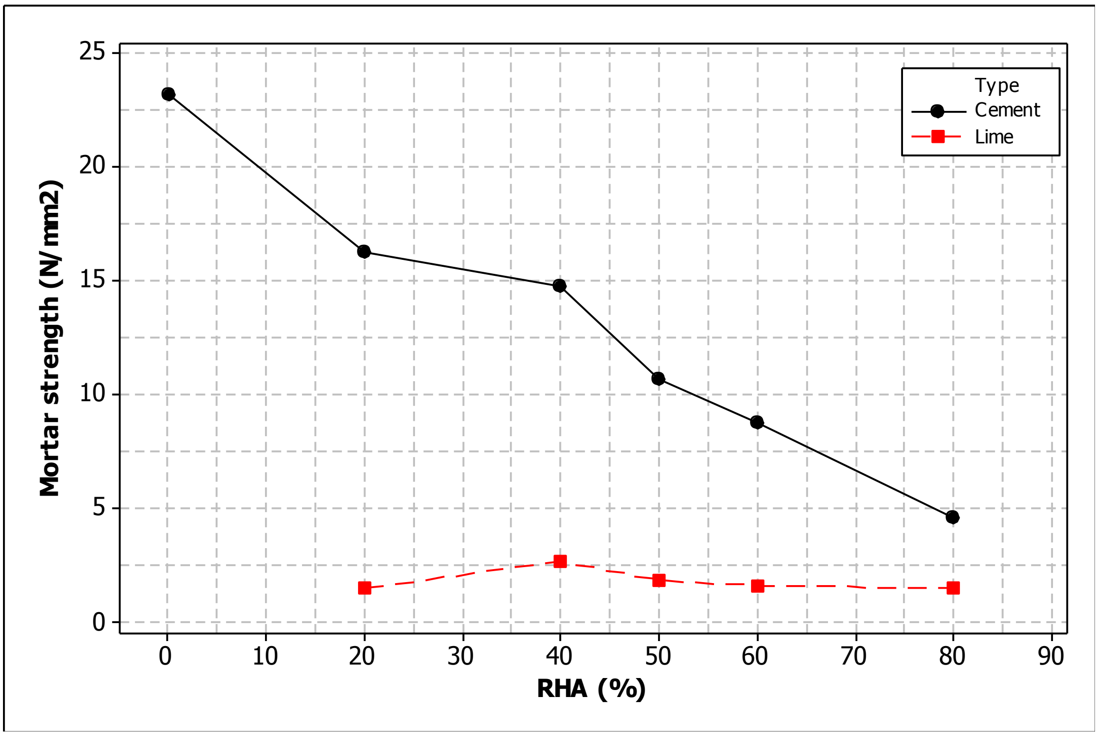


Figure 4. 28: : Comparison of Mortar Strength at 28 days for Slurry Ratio (Liquid: Solid) 0.625 for Varying RHA (%) to Cement (%) and RHA (%) to Lime (%)

Table 4. 50: Comparison of Mortar Strength at 28 Days for Slurry Ratio (Liquid: Solid) 0.625 for Varying RHA (%) to Cement (%) and RHA (%) to Lime (%)

Rha (%)	**Lime (%) Or Cement (%)**	**Mortar Cube Strength at a Curing Age of 28 Days For Slurry Ratio (Liquid: Solid) 0.625 (N/Mm2) [Mean ± Se]**	
		Mortar Cube Strength When a RHA- Lime Slurry Was Used	**Mortar Cube Strength When a RHA- Cement Slurry Was Used**
0	**100**	Dissolved at 28 Days	23.16± 0.81
20	**80**	1.48± 0.04	16.21± 0.51
40	**60**	2.65± 0.14	15.97± 0.33
50	**50**	1.82± 0.23	10.63± 0.41
60	**40**	1.58± 0.01	8.72± 0.46
80	**20**	1.47± 0.08	4.58± 0.17

Figure 4. 29: Part of the coating obtained on the surface of RCA when using RHA-lime can be easily washed off after air drying it for 24 hours

Figure 4. 30: Part of the coating obtained on the surface of RCA when using RHA-lime gets removed very easily

4.3. Test Results Obtained From the Concrete Specimens Made With the Treated RCA

4.3.1. Test Results of Concrete Specimens Made With the Best Scenarios of Treated RCA

4.3.1.1. Slump Test Results

When concrete is being compacted the entrapped air in the concrete mix gets removed. Hence in order to achieve dense compaction of the concrete high amounts of entrapped air need to be eliminated. Mainly the work done to compact a given concrete mix is to overpower the internal friction formed between the particles of the concrete mix and the surface friction formed between the surface of the reinforcement or of the mould and the concrete mix. The work done to vibrate the concrete mix can be divided in to two types. That is the work done to overpower the internal friction and surface friction which is considered as the ‘useful’ part of work and the work done to vibrate the mould and to vibrate the concrete that is already fully compacted is considered as the ‘wasted’ part of work. According to Neville (2011), in order to achieve a full compaction the amount of useful internal work needed can be said to be the workability of the concrete mix.

Workability is not only a property of fresh concrete it has a direct effect on the hardened concrete properties as well. To achieve a maximum compaction the concrete needs to be workable. The degree of compaction is proportional to the resulting strength. When voids are present in concrete it adversely affects its strength (Neville, 2011). Voids present in concrete are either due to the space left behind after the excess water were removed or due to entrapped air bubbles.

The main factor that affects the workability of a mix is the amount of water present in the mix. But when the amount of water present in the mix and other mix proportions are kept constant the workability of the mix mainly depends upon the characteristics of the aggregate. Such as its shape, surface texture, maximum size of the aggregate and its grading. According to Neville (2011), when a high water cement ratio is used in a concrete mix a finer grading is required in order to achieve a high workable mix.

The affect the properties of aggregates have on the workability of the concrete mix reduces as the richness of the mix increases. According to Neville (2011) the affect the properties of aggregates have on the workability of the concrete mix is negligible when the aggregate to cement ratio is as lesser as 2 or 2.5. According to the mix design used in the current study the aggregate to cement ratio is approximately 4.91, which indicates that the properties of the aggregates used to make the concrete specimens have a strong effect on the workability of the concrete mix.

It can be clearly seen in Figure 4.31 that even though RCA was used in a SSD condition when mixing it with the other constituent materials to make the concrete, the slump achieved was very low. This is mainly due to the resistance the concrete made with RCA has against the slump, due to its rough surface texture and its angular particle shape. By observing Figure 4.32 and Figure 4.33 it can be seen that the rough surface texture of RCA can be easily removed by the proposed treatment method. But when comparing the TRCA obtained after treating RCA with a slurry ratio of 0.625 containing a RHA: cement ratio of 20%: 80% given in Figure 4.34, and that treated with a slurry ratio of 0.625 containing a RHA: cement ratio of 40%: 60% given in Figure 4.33, it can be seen that when the amount of RHA present in the slurry is increased the surface of the TRCA gets rougher and more porous.

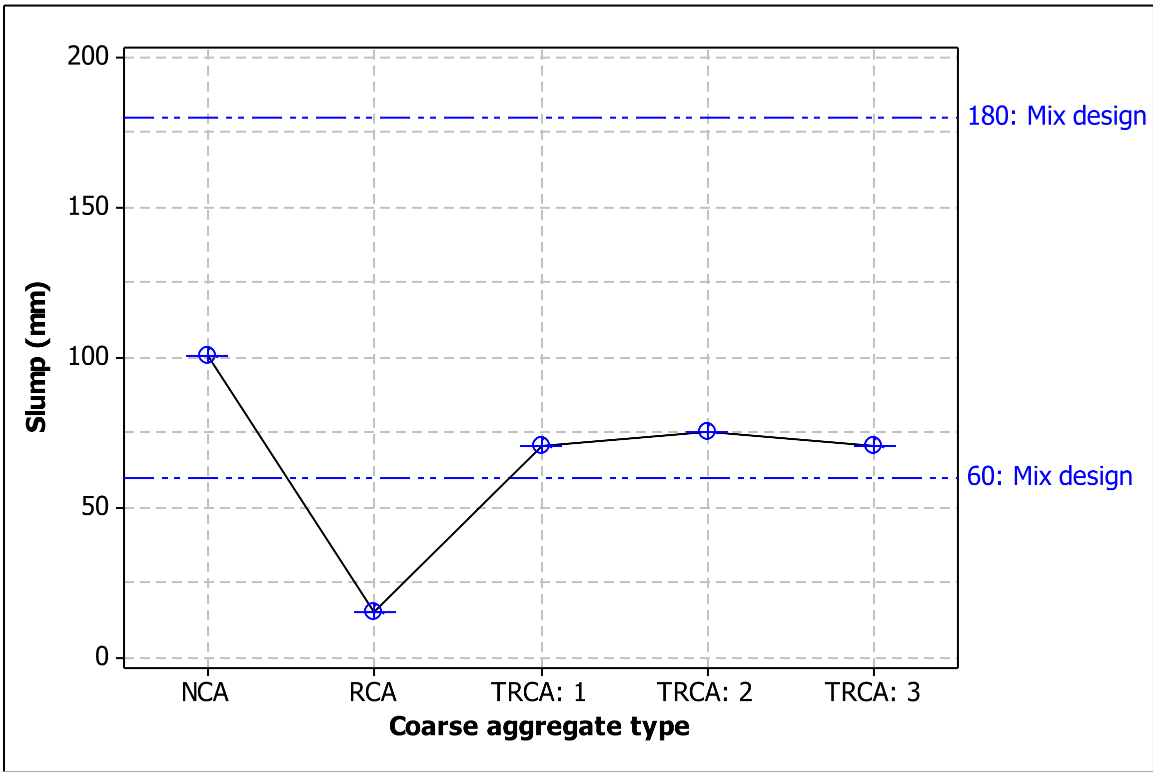


Figure 4. 31: Slump Test Results of Fresh Concrete made with the Best Scenarios of Treated RCA

The BRE mix design was calculated in order for the slump of the fresh concrete to be between 60- 180mm. When analyzing the data shown in Figure 4.31 and Table 4.51, it can be clearly seen that the slump of the concrete made with the best surface treatment scenarios have all achieved a slump within the specified range. Hence it is evident that when RCA is treated with the best surface treatment scenarios the negative impact it has on the fresh concrete properties can be negated.

Table 4. 51: Slump Test Results of Fresh Concrete Made With the Best Scenarios of Treated RCA and Their Respective Water Absorption Values at a Curing Age of 7 Days

Type of Coarse Aggregate		**Slurry Ratio (Liquid: Solid)**	**RHA: Cement (%:%)**	**Slump (Mm) [Mean ± SE]**	**Water Absorption (%)[Mean ± SE]**
NCA		-	-	100	0.39 ± 0.01
RCA		-	-	15	6.01 ± 0.06
TRCA	TRCA: 1	1.500	0%: 100%	70	3.53± 0.09
	TRCA: 2	0.875	20%: 80%	75	3.99± 0.25
	TRCA: 3		40%: 60%	70	4.33± 0.01

Figure 4. 32: Untreated RCA

Figure 4. 33: A Treated RCA Sample [Slurry Ratio = 0.625, RHA (%): Cement (%) = 40:60]

Figure 4. 34: A Treated RCA Sample [Slurry Ratio = 0.625, RHA (%): Cement (%) = 20:80]

When observing the data given in Table 4.51, it can be clearly seen that the slump of the fresh concrete made with the TRCA's, NCA and RCA are inversely proportional to their respective water absorption values. The correlation coefficient between the slump of the fresh concrete made with the TRCA's, NCA and RCA and the water absorption of the TRCA's, NCA and RCA is -0.448 having a P-value of 0.045. It can be confirmed with a 95% confidence that the correlation coefficient between the slump of the fresh concrete made with the TRCA's, NCA and RCA and the water absorption of the TRCA's, NCA and RCA is significantly different from zero since the P-value is 0.045 (<0.05). Furthermore it can be stated that there is a negative correlation between the slump of the fresh concrete made with the TRCA's, NCA and RCA and the water absorption of the TRCA's, NCA and RCA which confirms the data presented in Table 4.51. It should be highlighted that even though the aggregate types used to make the concrete specimens were in their SSD condition the water absorption of the aggregate type had a direct effect on the slump of the fresh concrete made with that respective aggregate type.

4.3.1.2. Compressive Strength Test Results

The BRE mix design was calculated in order to achieve a concrete that had a specified characteristic strength of 30 N/mm^2 at a curing age of 28 days. According to Figure 4.35 and Table 4.52 it can be clearly seen that the concrete specimens made with the TRC’s that were coated with the best surface treatment methods have all achieved strength greater than 30 N/mm^2. It can be further highlighted that the concrete specimens made with the TRCA’s have all achieved strength much greater than the concrete cubes made with NCA. When observing Figure 4.35 it can also be distinctively seen that the compressive strength of the concrete cubes made with RCA have achieved strength of 29.22 ± 0.59 N/mm^2 (≈ 30 N/mm^2). Furthermore it is important to note that 100% of RCA and TRCA’s were used to make the respective concrete specimens.

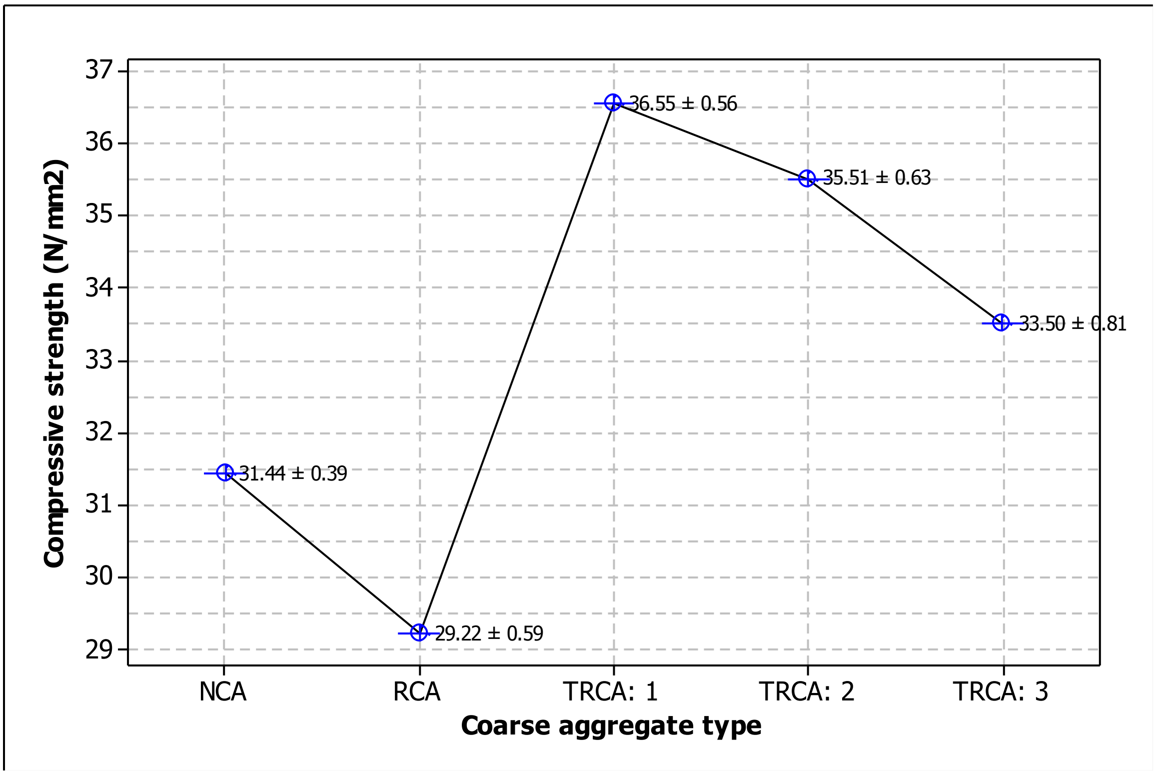


Figure 4. 35: Variation of Compressive Strength of Concrete made with Different Aggregate Types

Table 4. 52: Test Results of Concrete Specimens Made With the Best Scenarios of Treated RCA

Type of Coarse Aggregate		**Slurry Ratio (Liquid: Solid)**	**RHA: Cement**	**Compressive Strength at 28 Days (N/Mm2) [Mean ± SE]**
NCA		-	-	31.44 ± 0.39
RCA		-	-	29.22 ± 0.59
TRCA	TRCA: 1	1.500	0%: 100%	36.55 ± 0.56
	TRCA: 2	0.875	20%: 80%	35.51 ± 0.63
	TRCA: 3		40%: 60%	33.50 ± 0.81

The strength of concrete mainly depends on the structure of the hydrated cement paste. Hence it is said that by analyzing the strength of concrete a good understanding of the quality of it can be acquired.

The water present in a concrete mix is generally from two sources. They are the water added to the mix and the water present in the aggregate at the time it is added in to the mix. The water held by the aggregate is in the pore structure of the aggregate and in some instances is present on the surface of the aggregate as free water. The water present as free water on the surface of the aggregate is as similar to that been added directly to the mix. If the aggregate is not saturated there is a high tendency of part of the water been added in to the mix been absorbed by the pores that are filled with air during the initial half-hour after mixing. Since RCA and TRCA have a very high water absorption with respect to NCA it was decided to add the coarse aggregates used to produce concrete in their SSD condition.

Entrapped air, entrained air, capillary pores and gel pore are voids found in concrete. The volume of these voids has a direct effect on the strength of the concrete. The old attached mortar on the surface of RCA is very porous hence the concrete produced by it will have a very porous interfacial transition zone (ITZ) further affecting the strength of the concrete. But it can be seen by observing Figure 4.35, that the concrete produced by 100% of RCA has also achieved strength of 29.22 ± 0.59 N/mm^2. According to various studies carried out on RCA when 100% of RCA is used to produce concrete the strength it achieves at 28 days is usually very much lesser than the designed strength. In the current study these conclusions are rejected. Since even though RCA has a porous attached mortar around its surface it can still be used to produce a high strength concrete even by replacing 100% of NCA with RCA. The main reason for the inferior RCA to have achieved a good strength at 28 days is its rough surface and is angular shape. According to Neville (2011) the properties of the coarse aggregates have a large influence on the development of cracks in the concrete due to the stress been imposed on it. That is when rough and angular coarse aggregates are used the concrete tends to crack at higher stresses than when rounded and smooth coarse aggregates are used. Since the surface properties and the shape of the coarse aggregates have an influence on the mechanical interlocking of the coarse aggregates present in concrete. The surfaces of TRCA's are smoother than that of untreated RCA. As the slurry been used to coat the RCA gets thinner and/or as the percentage of cement been replaced with RHA increases the surface of TRCA's gets rougher.

The region between the hardened cement paste and the coarse aggregate particles is known as the transition zone. It is generally a very thin layer having a thickness of 10-50 μm. The transition zone is very much different from the bulk of the cement paste (mortar matrix). It is mainly due to the fact that the dry fine cement particles cannot get densely packed against the coarse aggregate particles during mixing. This effect is similar to the 'wall-effect' that occurs at the surface of cast concrete. Hence there is less cement present near the coarse aggregate particles to undergo the hydration reaction and fill the initial voids been made. Therefore the transition zone is more porous and it contains large C-H crystals than the mortar matrix. Even though the transition zone is very thin than the other two phases present in concrete the effect it has on the properties of the concrete is great. The transition zone is weaker than the aggregate phase and the hardened cement phase of the concrete. The porous and large C-H crystals create smooth planes for micro cracks to go through. The micro cracking of concrete is initiated at the transition zone. This can be negated with the addition of pozzolanas. Since the pozzolanic reaction would occur with time between the large C-H particles present in the transition zone and the pozzolan. The pozzolanic reaction will form additional C-S-H and will remove the large C-H crystals which will produce a denser transition zone.

By coating RCA with slurry that contains a mixture of cement and/or RHA the transition zone of the concrete produced with it can be made denser due to the presence of firmly packed hydrated cement and/or RHA coating on the surface of RCA. Since the TRCA's used to produce the concrete were only cured for time duration of 7 days the hydration reactions and the pozzolanic reactions haven't completely taken place. The compressive strength of the concrete specimens made with the selected TRCA's shown in Figure 4.35, is greater than that made with 100% NCA. This is probably due to the dense transition zone created in the concrete produced with TRCA's due to the cement and/or RHA coating around the surface of RCA and the somewhat rough surface texture and angular particle shape of the TRCA's used.

4.3.2. Test Results of Concrete Specimens Made With Treated RCA That Had Been Cured For 24 Hours, Which Had Been Coated With Varying Slurry Ratios and Varying RHA-Cement Ratios

4.3.2.1. Slump Test Results

The BRE mix design was calculated in order for the slump of the fresh concrete to be between 60- 180mm. When analyzing the data shown in Figure 4.36 and Table 4.53, it can be clearly seen that the slump of the concrete made with the TRCA that had been cured for 24 hours, which had been coated with varying slurry ratios and varying RHA-Cement ratios as shown in Table 3. 13, have all achieved a slump lesser than the specified range but greater than that of untreated RCA. Hence it can be said that when RCA is treated with the treatment scenarios given in Table 3. 13, and are cured for a time duration of 24 hours, the negative impact the use of RCA has on the fresh concrete properties can be negated to some extent.

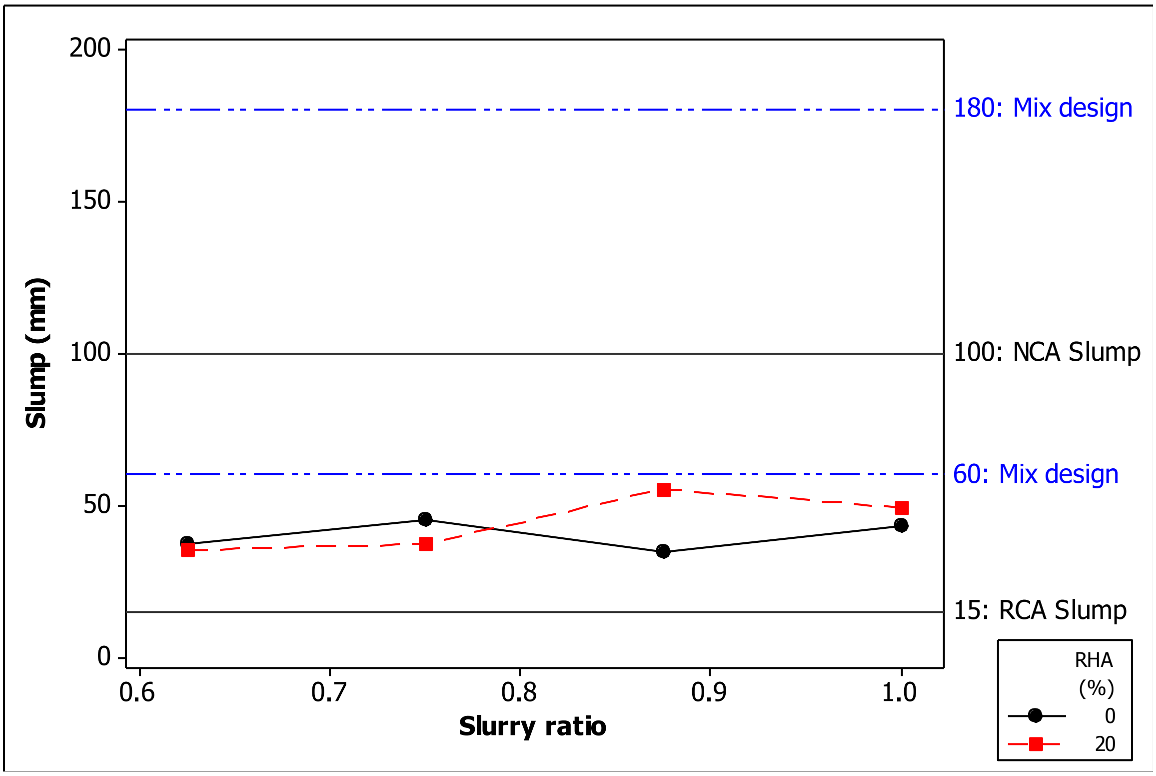


Figure 4. 36: Slump Test Results of Fresh Concrete made with Treated RCA, which had been Coated with Varying Slurry Ratios and Varying RHA-Cement Ratios

Table 4. 53: Slump Test Results of Fresh Concrete Made With Treated RCA, Which Had Been Coated With Varying Slurry Ratios And Varying RHA-Cement Ratios

RHA (%)	**Cement (%)**		**Slurry Ratio (Liquid: Solid)**			
			0.625	**0.75**	**0.875**	**1.00**
0	**100**	Slump (Mm) [Mean ± Se]	37	45	34	43
		Water Absorption (%) [Mean ± Se]	5.51± 0.15	4.58± 0.15	5.12± 0.16	4.56± 0.38
20	**80**	Slump (Mm) [Mean ± Se]	35	37	55	49
		Water Absorption (%) [Mean ± Se]	6.00± 0.19	5.51± 0.16	4.34± 0.09	4.76± 0.23

When observing the data given in Table 4.53, it can be clearly seen that the slump of the fresh concrete made with the TRCA's are inversely proportional to their respective water absorption values. The correlation coefficient between the slump of the fresh concrete made with the TRCA's and the water absorption of the TRCA's is -0.818 having a P-value of 0.013. It can be confirmed with a 95% confidence that the correlation coefficient between the slump of the fresh concrete made with the TRCA's and the water absorption of the TRCA's are significantly different from zero since the P-value is 0.013 (<0.05). Furthermore it can be stated that there is a negative correlation between the slump of the fresh concrete made with the TRCA's and the water absorption of the TRCA's which confirms the data presented in Table 4.53. It should be highlighted that even though the aggregate types used to make the concrete specimens were in their SSD condition the water absorption of the aggregate type had a direct effect on the slump of the fresh concrete made with that respective aggregate type.

4.3.2.2. Compressive Strength Test Results

The BRE mix design was calculated in order to achieve a concrete that had a specified characteristic strength of 30 N/mm^2 at a curing age of 28 days. According to Figure 4.37 and Table 4.54 it can be clearly seen that the concrete specimens made with the TRC's that were coated with the treatment scenarios given in Table 3.11, have all achieved strength greater than 30 N/mm^2. It can be further highlighted that the concrete specimens made with the TRCA's all except the scenario where slurry of 0.625 containing 20% of RHA and 80% of cement was used, have achieved strength much greater than the concrete cubes made with NCA. It should be highlighted that even by curing the TRCA's for a time period of 24 hours the compressive strength of the concrete made with them can achieve strength greater than 30 N/mm^2 at a curing age of 28 days. Furthermore it is important to note that 100% of TRCA's were used to make the respective concrete specimens.

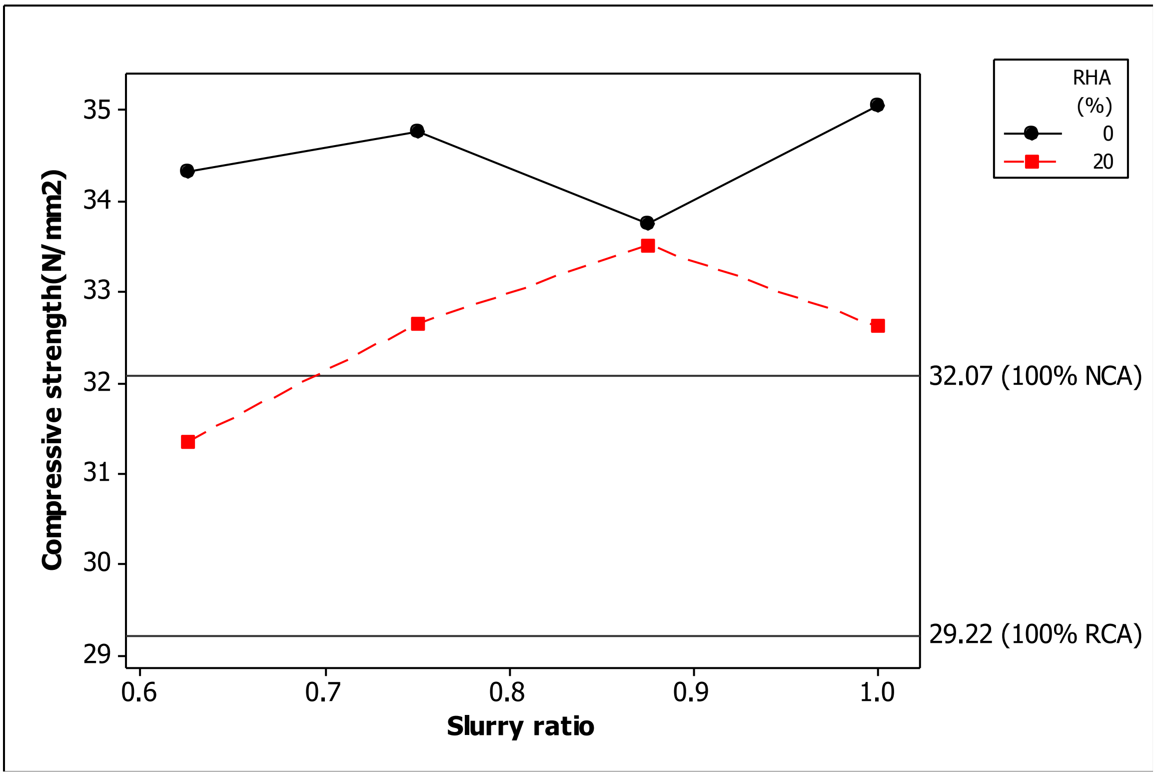


Figure 4. 37: Test Results of Concrete Specimens made with the Treated RCA, which had been Coated with Varying Slurry Ratios and Varying RHA-Cement Ratios

Table 4. 54: Test Results of Concrete Specimens Made With the Treated RCA, Which Had Been Coated With Varying Slurry Ratios and Varying RHA-Cement Ratios

Compressive Strength at 28 Days (N/Mm2) [Mean ± SE]					
RHA (%)	**Cement (%)**	**Slurry Ratio (Liquid: Solid)**			
		0.625	**0.75**	**0.875**	**1.00**
0	**100**	34.33± 0.40	34.77± 0.25	33.76± 0.42	35.06± 0.09
20	**80**	31.35± 0.55	32.65± 0.60	33.51± 0.30	32.62± 0.13

4.4. Cost Analysis

In order to coat 2 kg of RCA the amount of liquid that was required =300 g

Therefore the amount of solid needed to coat 1 kg of RCA by the treatment methods being selected are given in Table 4.55.

Table 4. 55: The Amount of Solid Needed to Coat 1 Kg Of RCA

RHA (%)	Cement (%)	Slurry Ratio	Total Solid Content Needed to Coat 2 Kg of RCA (G)	RHA Content Needed to Coat 2 Kg of RCA (G)	Cement Content Needed to Coat 2 Kg of RCA (G)
0	**100**	**1.5**	200	0	200
20	**80**	**0.875**	342.86	68.57	274.29
40	**60**			137.14	205.72

1 cube of RCA = 100 ft^3 = 2.83 m^3

Bulk density (Loose) of RCA = 1299.33 kgm^{-3}

(According to observations made by analyzing the test results)

Hence the weight of 1 cube of RCA = 2.83 m^3 X 1299.33 kgm^{-3} = 3677.10 kg

Therefore the amount of solid needed to coat 1 cube of RCA by the treatment methods being selected are given in Table 4.56.

Table 4. 56: The Amount of Solid Needed to Coat 1 Cube of RCA

RHA (%)	Cement (%)	Slurry Ratio	Total Solid Content Needed to Coat 2 Kg of RCA (G)	Total Solid Content Needed to Coat 1 Cube of RCA (Kg)	RHA Content Needed to Coat 1 Cube of RCA (Kg)	Cement Content Needed to Coat 1 Cube of RCA (Kg))
0	**100**	**1.5**	**200**	367.71	0	367.71
20	**80**	**0.875**	**342.86**	630.37	126.07	504.30
40	**60**				252.15	378.22

Price of 1 cube of RCA (when purchasing from the COWAM center)= 5500 LKR

(Due to inadequate data the market price of 1 cube of RCA was taken in to consideration when calculating the cost, but it needs to be kept in mind that the actual manufacturing cost of RCA will be much lower)

Transportation cost= 45 LKR/km

Distance between Dadalla Cemetery to University of Moratuwa (via Southern Expressway/E01 and A2)= 105 km

Transportation cost of RCA= 45 LKR/km X 105 km = 4725 LKR

(Transportation cost of RCA is considered as a variable and needs to be brought to a minimum value in order to make the treatment method cost effective. Hence the crushing process of RCA was included in to the treatment plant being proposed.)

Total cost of 1 cube of RCA= Market price of 1 cube of RCA + Transportation cost of RCA = 5500 LKR + 4725 LKR = 10225 LKR

Price of 50 kg of cement (1 bag)= 870 LKR

Cost of RHA= 0 LKR

(Rice husk is a waste product obtained from the milling process of rice. Rice husk is used as a fuel in the parboiling process of rice. Therefore RHA can be obtained from rice mills that carry out parboiling of rice, for free)

Distance between Ampara to University of Moratuwa (via Colombo-Batticaloa highway)= 326 km

Transportation cost of RHA= 45 LKR/km X 326 km = 14670 LKR

(From Ampara to the University of Moratuwa)

Grinding of RHA was carried with the use of a LAAV machine. It was ground for 1500 revolutions for a time duration 1.5 hours. The power consumption of the LAAV machine was 740 W.

The power consumed in order to grind 6 kg of RHA= 740 X 10^{-3} kW X 1.5 h = 1.11 kWh

The tariff plan for the monthly consumption of electricity specified by the Ceylon Electricity Board is given in Table 4.57.

Table 4. 57: Tariff Plan for the Monthly Consumption of Electricity Specified By the Ceylon Electricity Board

Monthly Consumption kWh	Unit Charge (LKR/ kWh)	Fixed Charge (LKR/Month)
0-60	**7.85**	**N/A**
61-90	**10.00**	**90.00**
91-120	**27.75**	**480.00**
121-180	**32.00**	**480.00**
>180	**45.00**	**540.00**

Source: (Ceylon Electricity Board, 2014)

Hence the cost undergone to grind the required quantities of RHA is shown in Table 4.58.

Table 4. 58: Cost Undergone to Grind the Required Quantities of RHA

RHA (%)	Cement (%)	Slurry Ratio	RHA Content Needed to Coat 1 Cube of RCA (kg)	Power Consumed to Grind RHA (kWh)	Cost Undergone to Grind RHA (LKR)
0	**100**	**1.5**	**0**	0	0
20	**80**	**0.875**	**126.07**	23.32	183.06
40	**60**		**252.15**	46.65	366.20

The total cost of RHA= Cost undergone to produce RHA + Cost undergone to grind RHA + Transportation cost of RHA

Hence the total cost of RHA is given in Table 4.59.

Table 4. 59: Total Cost of RHA

RHA (%)	Cement (%)	Slurry Ratio	Cost Undergone to Grind RHA (LKR) [X]	Transportation Cost of RHA (LKR) [Y]	Cost to Produce RHA (LKR) [z]	Total Cost of RHA (LKR) [= X+Y+Z]
0	**100**	**1.5**	-	-	Free	-
20	**80**	**0.875**	183.06	14670		14853.06
40	**60**		366.20			15036.2

The cost it will take to treat 1 cube of RCA with the selected slurry scenarios is shown in Table 4.60.

The transportation cost of RHA is considered as a variable and needs to be brought to a minimum value in order to make the treatment method cost effective, since it is approximately 98% of the total cost undertaken to process RHA. Hence the entire process of converting rice husk in to ground RHA was included in to the treatment plant being proposed. This will negate the unnecessary cost of transporting RHA from far off locations (e.g. Ampara).

Table 4. 60: The Cost it Will Take to Treat 1 Cube of RCA

RHA (%)	Cement (%)	Slurry ratio	Total cost of RHA Needed (LKR) [X]	Cost of Cement Needed (LKR) [Y]	Cost of 1 Cube of RCA (LKR) [Z]	Total Cost to Treat RCA (LKR) [= X+Y+Z]
0	**100**	**1.5**	0	6398.15	10225	16623.15
20	**80**	**0.875**	14853.06	8774.82		33852.88
40	**60**		15036.2	6581.03		31842.23

Cost of 1 cube of NCA= 7800 LKR

According to the cost analysis of the current study it can be seen that the cost in order to treat 1 cube of RCA with the proposed treatment method is significantly greater than the price of 1 cube of NCA available in the market. It is evident that the treatment method carried out in the laboratory was not cost effective.

On the contrary If we look at the entire process than only concentrate on these values it is clear that there are some major cracks that need to be addressed in order to make the treatment method cost effective. As noted out earlier the transportation cost of RCA and RHA and the market price of 1 cube of RCA were key components that made this treatment process ineffective monetary wise.

According to Table 4.63, it can be clearly seen that the cost of RHA, cement and RCA are all very high.

The cost of RHA needed to treat RCA according to Table 4.63, is approximately 43-48 % of the total cost needed to treat 1 cube of RCA. When considering the cost of

RHA it is mainly made up with the cost undergone to produce RHA, cost undergone to grind RHA and the transportation cost of RHA. The transportation cost of RHA is 14670 LKR which is approximately 98% of the total cost of RHA. hence in order to reduce the total cost of RHA a major proportion of the transportation cost needs to be cut down. It can be done by either treating the RCA at Ampara itself or burning the rice husk at the treatment plant of RCA. By carrying out the latter method a RHA that has a higher quality can be produced due to standardizing the burning conditions of the rice husk. The use of a LAAV machine to grind RHA is not recommended since the fineness of the ground RHA is greater than that of cement. Therefore an industrial ball mill is recommended. The power consumption of an industrial ball mill will vary between 75-1800 kW depending on the type of ball mill being used and its capacity. This will directly increase the cost of grinding. According to theoretical analysis in order for RHA to demonstrate good pozzolanic properties it needs to be burned under controlled burning and its mean particle size needs to be lesser than that of cement. Therefore according to literature, by improving the quality of RHA a higher percentage of RHA can be used to treat RCA thereby reducing the amount of cement being used to treat RCA. The quality of the RHA and the fineness of the ground RHA used in the research were not up to the mark, in order to make the best use of the pozzolanic properties present in RHA. it can be recommended that ground RHA obtained from a controlled system, to be tested in the future to analyze whether a higher percentage can be used in order to replace cement used to treat RCA.

The cost of cement needed to treat RCA is approximately 38-20 % of the total cost needed to treat 1 cube of RCA.

The cost of RCA is mainly made up of the transportation cost and the market price of RCA. The transportation cost is approximately 46 % of the total cost of RCA which needs no to be cut down in order to carry out a cost effective treatment method. The current market price of RCA is approximately 0.7 times that of NCA. Further studies need to be carried out regarding the actual cost undertaken to convert concrete debris in to RCA. Since the market price of RCA is very much similar to NCA hence the objective of using a low cost sustainable alternative material for NCA will be lost.

When RHA was used to treat RCA the transportation cost is approximately 57-60 % of the total cost undergone to treat RCA and when cement alone was used to treat RCA the transportation cost is approximately 28 % of the total cost undergone to treat RCA. It is evident that the transportation cost of RHA and RCA plays a vital role when calculating the cost undertaken to treat RCA.

In Table 4.61, the cost undertaken to treat RCA was calculated by negating the transportation cost of RHA and RCA and the actual value undertaken to process RCA. It can be clearly seen that the total cost to produce 1 cube of TRCA is still very much higher than that of NCA. This is mainly due to the higher percentage of cement being used to treat 1 cube of RCA.

Table 4. 61: The Cost Undertaken to Treat RCA Calculated by Negating the Transportation Cost of RHA and RCA and the Actual Value Undertaken to Process RCA

RHA (%)	Cement (%)	Slurry Ratio	Total Cost of RHA Needed (Lkr) [X']	Cost of Cement Needed (Lkr) [Y]	Actual Cost of 1 Cube of RCA (Lkr) [Z']	Total Cost to Treat RCA (Lkr) [= X'+Y+Z']
0	**100**	**1.5**	0	6398.15	2,500	8,898.5
20	**80**	**0.875**	183.06	8774.82		11,457.88
40	**60**		366.20	6581.03		9,447.23

4.5. Proposal For A Treatment Plant to Treat Recycled Coarse Aggregates (RCA) Using the Proposed Treatment Method

Selective demolition of old structures and waste accumulated after construction activities need to be carried out in order to efficiently implement the treatment method being proposed. Hence plastic, wires, switches, regulators, wood, glass, iron and steel, roof tiles, floor tiles and etc. can be easily recovered and recycled. The remaining concrete debris can be transported to the recycling plant.

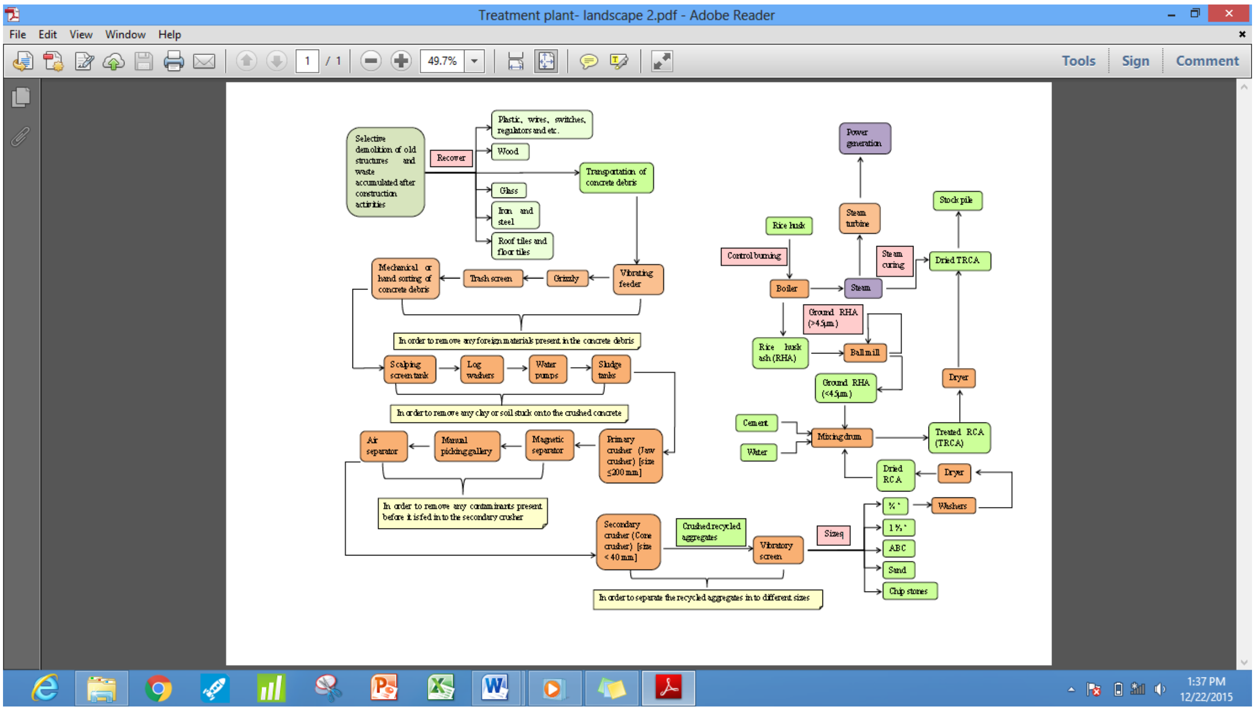
At the recycling plant in order to remove any foreign materials present in the concrete debris it can be initially sent through a vibrating feeder, grizzly, trash screen respectively and afterwards hand sorting or mechanical methods can be implemented to further remove any foreign materials from the concrete debris. Afterwards the crushed concrete is proposed to be sent through a scalping screen tank, log washers, water pumps and sludge tanks respectively in order to remove any clay or soil stuck on to the crushed concrete.

Afterwards the concrete will be sent through a primary crusher (Jaw crusher) [size ≤200 mm], magnetic separator, manual picking gallery and an air separator respectively in order to remove any contaminants present before it is fed in to the secondary crusher. The crushed aggregates will be sent through a secondary crusher (Cone crusher) [size < 40 mm]. The crushed recycled aggregates will then be sent through a vibratory screen in order to separate the recycled aggregates in to different sizes of ¾’, 1 ½’, ABC, sand and chip-stones. The treatment method proposed in this study is for RCA having a size fraction of ¾’.

The aggregates having the size fraction of ¾’, is then sent through a washer and afterwards a dryer in order to remove any dust particles on the surface of RCA. The dried RCA will then be sent to a mixing drum where it will be mixed with the required proportions of cement, ground RHA and water for a specific time (10 minutes). The treated RCA will then be sent through a dryer and afterwards will be steam cured for specific time duration. The treated RCA will then be placed in stock piles ready for transportation. The steam required for the treatment of RCA will be obtained from the processing of rice husk.

Rice husk will be transported from the nearest rice mill hence reducing the transportation cost. It will be used as fuel for boilers to produce steam. It should be highlighted that the burning of rice husk needs to be carried out in a controlled system. The steam produced here will be used to cure the treated RCA and to generate power using a steam turbine. The power generated from the steam turbine will be used in the treatment plant. The rice husk ash obtained after burning the rice husk will be ground by a ball mill to a particle size finer than cement.

A schematic diagram of the treatment plant proposed to treat recycled coarse aggregates (RCA) using the treatment method studied under this research is shown in Figure 4.38.



In order to remove any foreign materials present in the concrete debris

In order to remove any clay or soil stuck onto the crushed concrete

In order to remove any contaminants present before it is fed in to the secondary crusher

In order to separate the recycled aggregates in to different sizes

Figure 4. 38: Flow Diagram of the RCA Treatment Plant

Chapter 05:CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

In this study the surface of RCA was coated with slurries that contained varying proportions of rice husk ash (RHA), water and lime or cement. The slurry ratios used in the research were 0.625, 0.75, 0.875, 1.000, 1.250, 1.500 and 2.000. The solid compositions in the slurry were varied as needed by varying the RHA to lime or cement composition as followed 0%:100%, 20%:80%, 40%:60%, 50%:50%, 60%:40% and 80%:20%. The treated recycled coarse aggregate (TRCA) coated with a RHA-lime slurry had been cured for 24 hours and their water absorption percentage were tested. The TRCA coated with RHA-cement slurry had been cured for 3days, 7 days, 14 days and 28 days and their water absorption percentages were tested. Mortar cubes containing various proportions of water, RHA and lime ratios having the dimensions of 50X50X50 mm3 were made and cured for 28 days and their compressive strength were tested for the respective curing ages. Mortar cubes containing various proportions of water, RHA and cement ratios having the dimensions of 50X50X50 mm3 were made and cured for 7 days, 14 days and 28 days and their compressive strength were tested for the respective curing ages. Concrete cubes were made with concrete of grade 30 having a water-cement ratio of 0.55, which were produced with three selected scenarios of TRCA, RCA and NCA. The compressive strength of theses concrete cubes were tested after a curing age of 28 days.

RHA-lime slurry and RHA-cement slurry having varying concentrations were used to treat RCA. As a whole when observing the test results it can be seen that the behavior of the water absorption of TRCA with the thickness of the slurry ratio and the percentage of cement been replaced with RHA is somewhat similar. That is as the percentage of lime or cement been replaced with RHA increases the water absorption of the TRCA’s increases and as the slurry gets thinner the water absorption of TRCA’s reduces. But when RHA-cement slurry was used to coat RCA it was observed that as the slurry gets even thinner beyond a certain extent the water absorption of the TRCA’s increases. Even though the water absorption of RCA’s can be reduced by coating it with RHA-lime slurry or RHA-cement slurry, the question lies as to what is the best combination of materials that should be used in order to get a significant reduction in the water absorption of RCA’s. The water absorption of NCA and untreated RCA were found out to be 0.39% and 6.01% respectively.

When RCA’s were coated with RHA-lime slurry the maximum reduction in the water absorption percentage of TRCA’s were obtained at a slurry ratio of 1.00 within the range of 4.30-5.40%. but when considering RCA’s that were coated with RHA-cement slurry the maximum reduction in the water absorption percentage of TRCA’s were obtained at a slurry ratio of 1.50 when 100% cement was used in the slurry and 0.875 when a mixture of RHA and cement was used in the slurry, they were within the range of 3.50-4.45%. Furthermore when analyzing the strength of the mortar cubes made with RHA-lime slurries and RHA-cement slurries it is evident that the mortar cubes made with the latter type of slurries exhibit a better strength than those made with RHA-lime slurries. The strength of the mortar cubes made with a specific slurry can be used to predict the strength of the coating around the surface of RCA that had been treated with that specific slurry. Therefore it can be clearly seen that if TRCA’s coated with RHA-lime slurries are used to produce structural concrete it would cause a lot of detrimental impacts on the performance of concrete due to the weak RHA-lime coating around its surface. Hence it is best to treat RCA with RHA-cement slurry.

The next area that needs to be clarified is what are the slurry ratios (i.e. liquid: solid), the RHA-cement ratios and the curing that would give the optimum reduction in the water absorption of RCA. According to the test results these two parameters can be obtained by analyzing the test results of RCA treated with a slurry that contained 100% cement and RCA treated with a slurry that contained a mixture of RHA and cement. In order to identify the optimum amount of RHA that can be used to replace cement, the behavior of the mortar cubes made with the varying RHA-cement slurries were taken in to consideration.

When RCA is treated with slurry containing 100% of cement a maximum reduction in the water absorption of RCA can be achieved when a slurry ratio of 1.5 is used.

According to the graphical presentation it can be seen that this can even be within the range of 1.5-1.6. When RCA is treated with slurry containing a mixture of RHA and cement a maximum reduction in the water absorption of RCA can be achieved when a slurry ratio of 0.875 is used. According to the graphical presentation it can be seen that this can even be within the range of 0.875-1.00.

As the RHA percentage used to replace cement in the slurry increases, the water absorption of the TRCA increases and the strength of the coating reduces. Hence it's best not to replace RHA beyond 40% in the solid composition of the specific slurry being used to treat RCA. Furthermore when RCA is coated with thick slurries the amount of RHA present in the slurry has a significant negative impact on the water absorption of TRCA. That is when the amount of RHA present in the slurry increases the water absorption of the TRCA's increases and in some instances is greater than untreated RCA. But it was observed that the water absorption of TRCA's can be significantly lesser than that of RCA when it's been coated with thin slurries even when the replacement of cement with RHA reaches up to 50%. This indicates that when a thin slurry is used to coat RCA a higher amount of cement can be replaced with RHA.

In most cases it was observed that the water absorption of TRCA's were lowest at a curing age of 7 days. Beyond a curing age of 7 days the water absorption of TRCA's tends to increase even after been cured for a time duration of 28 days. Hence it can be concluded that when RCA is treated using this method it is best not to cure the TRCA's beyond a curing age of 7days.

Furthermore when RCA is treated by using this treatment method the negative impact RCA has on the fresh and hardened concrete properties can be negated significantly.

The main question that arises when considering the cost analysis carried out is that the proposed treatment method is too expensive. Hence it is more economical to use NCA than TRCA. It should also be highlighted that the market price of RCA itself is very high it is almost as that of the market price of NCA. This really questions the cost effectiveness of using RCA as a suitable alternative material for NCA. The transportation cost of RHA and RCA is excessively high. If the transportation cost of the raw materials were negated and the pure cost to produce 1 cube of RCA was considered the total cost to produce 1 cube of TRCA was still very much higher than that of NCA. This is mainly due to the higher percentage of cement being used to treat 1 cube of RCA. In order to make the proposed treatment method cost effective and sustainable the percentage of RHA being used to treat RCA should be 70% or more. The grinding of RHA with the use of a LAAV machine can be carried out for a reasonably lower cost. On the contrary the effectiveness of using a LAAV machine to grind RHA is questionable since the fineness achieved is much higher than that of cement hence reducing the pozzolanic properties of RHA. To carry out an effective grinding of RHA an industrial ball mill is recommended but this will directly increase the cost of grinding.

5.2. Recommendations

The water absorption of RCA can be reduced by 2-3 % by coating it with RHA-cement slurry. A slurry ratio of 1.5 having a RHA-cement ratio of 0%- 100% and a slurry ratio of 0.875 having a RHA-cement ratio of 20 %-80 % and 40%- 60% are recommended to treat RC A in order to reduce its water absorption.

The RHA used in the study were not of the best quality since the RHA samples were obtained after the rice husk had undergone uncontrolled burning. Therefore further studies need to be carried out with RHA that was obtained from a controlled burning process. Where the temperature and burning time are fixed and known parameters.

Testing needs to be carried out with RHA samples that have been ground to a fineness of cement or fine than cement.

The RCA obtained from the COWAM center were a mixture of aggregates extracted from various types of parent concrete. The parent concrete has a direct effect on the attached mortar present on the RCA. Hence in order to reduce the variability of the RCA sample itself, it is recommended to crush a known grade of concrete and extract the RCA from it.

In order to treat RCA with the best treatment scenarios it can be observed that a high percentage of cement is being used hence increasing the cost and reducing the sustainability of the treatment method. Further studies need to be carried out by blending cement with supplementary cementing materials like fly ash, granulated blast furnace slag (GGBS), silica fume, rice husk ash (RHA), termite soil and metakaolin in order to reduce the amount of cement being used to treat RCA.

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Appendix – A

Details of the Tests Carried Out in the Research Study

Appendix – B

Calculations Performed to Obtain the Mix Design

Appendix – C

Photographs Taken During the Research Study