DEVELOPMENT OF RECYCLED AGGREGATE CONCRETE WITH PRISTINE GRAPHENE

BY

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Glossary of terms and abbreviations

NCA: Natural Coarse Aggregate

RCA: Recycled Coarse Aggregate

NAC: Natural Aggregate Concrete

RAC: Recycled Aggregate Concrete

ITZ: Interface Transition Zone

C&D: Construction and Demolition

SSSD: Saturated Surface Dry Density

SEM: Scanning Electron Microscopy

AS: Australian Standard

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Declaration

I certify that this thesis has been composed by the author and no portion of this thesis had been submitted for the award of another degree from any University.

Signed:

Dated: 1 November 2021

Executive Summary

This thesis research aimed at the development of recycled aggregate concrete with pristine graphene. This work was undertaken in response to the detrimental effect construction and demolition (C&D) waste has on the landfills and the continuous depletion of natural coarse aggregate. The process of converting the C&D waste into recycled coarse aggregate was seen as the best option to tackle the highlighted problems associated with C&D waste.

From research, pristine graphene was seen as the best nanomaterials that could be used to reinforce this recycled coarse aggregate that possesses lower mechanical properties than the natural coarse aggregate. The pristine graphene at different dosages i.e., 0.1%,0.2%,0.3% and 0.5% was introduced into recycled coarse aggregate and soaked for up to 24 hours for the pore spaces of the recycled coarse aggregate to be filled up with the solution of pristine graphene.

A mix of 6 batches of concrete specimen consisting untreated recycled aggregate concrete, treated recycled aggregate concrete and the conventional concrete were made. Mechanical and durability properties of concrete such as compressive strength, splitting tensile strength, drying shrinkage and water absorption tests was performed on these mixes. It was found that the addition of graphene helped in the increase in both compressive and tensile strengths of reinforced RAC. Mix N50R50P0.2% consisting 0.2% of pristine graphene was the optimum dosage and produced 60.74MPa which is 19% more than the untreated RAC mix. The effect of graphene was also seen in the water absorption and drying shrinkage of hardened concrete. The drying shrinkage of mix N50R50P0.3% containing 0.3% of graphene dose had the least shrinkage of 160 micro strain which 66% lower than the untreated RAC and 82% lower than the control mix. The water absorption on the other hand was reduced to 2.69% in mix N50R50P0.1% having 0.1% of pristine graphene. It was concluded that the use of recycled aggregate concrete should be encouraged in the construction industry in order to reduce landfill intake, environmental problems and the depletion of natural resources.

Chapter 1: INTRODUCTION

1.1 Background

Construction and Demolition (C&D) wastes are generated from activities arising from construction, renovation, and demolition (Zhao et al.2019). These C&D waste takes up valuable space on landfill and have some environmental effects on soil, water and air in the surrounding(Luo et al. 2019). In addition to that, the C&D wastes are associated to be one of the major consumers of natural resources leading to the increase of natural aggregates production from 21 billion tons in 2007 to 40 billion tons in 2014(Tam, Soomro &Evangelista 2018). According to (De Brito 2013), the construction industry having to be one of the largest industries in the world is responsible for major CO2 release into the atmosphere. Research has shown that concrete waste contributes to about 60% of C&D wastes and the development of this waste into recycled coarse aggregate(RCA) will not reduce the C&D going to the landfill but also replace the natural aggregate(NA) and then save if from depletion(Islam et al. 2019).Therefore the ideal way of solving the problem above is by recycling the concrete waste and use for concrete production.

However, it has been found through research that these concrete wastes when transformed into recycled coarse aggregate (RCA) are weaker than the natural coarse aggregate (NCA) (Luo et al. 2019). They offer high porosity, high water absorption rate, high saturated and bulk densities. In addition, they contain huge amount of cement paste and mortar attached on its surface(Xiao,Li &Poon 2012).(Xiao, Li & Poon 2012) revealed that recycled aggregate concrete (RAC) offers compressive and tensile strengths lower than the conventional concrete. In addition, the structural behaviour of RAC elements are weaker than the elements made of natural aggregates(Xiao et al. 2012).

Research has shown that the ideal way of solving the problems of RCA is by developing different techniques to improve the performance characteristics to have a lower porosity, lower water absorption rate, higher specific and saturated surface dry density(SSSD).Some studies have attempted the pre-treatment of the recycled aggregate by soaking in acidic solution(Tam, Tam & Le 2007) while some first modify the surface structure of recycled aggregate by impregnation with chemicals as a means of treatment (Zhao et al. 2013). However, with the rapid development of nanotechnology, nanomaterials which are of cheaper costs and which offers better treatment to recycled aggregate will greatly increase the utilization of recycled aggregate concrete(Luo et al. 2019).

1.2 Knowledge gap

There have been an increasing number of studies towards the improvement of the mechanical properties of recycled aggregate concrete with the addition of nanomaterials as reinforcement (Sumesh et al.2017). Many studies have done well by establishing the fact that these nanomaterials such as nano silica, carbon nanotubes etc. are good for strength improvement in RAC, however many studies have received minimal improvement in the mechanical and durability properties of recycled aggregate concrete.

This thesis will focus on the use of pristine graphene, which offers higher mechanical properties than other nanomaterials. Pristine graphene has tensile strength of approximately 130GPa,elastic modulus of 1000GPa,desnsity of 2200kg/m^3 and electrical conductivity of approximately 1000S/m (Chuah et al. 2014).

1.3 Aims and objectives

Aim

To develop a sustainable recycled aggregate concrete (RAC) that offers better or similar mechanical and durability properties to the conventional concrete.

Objectives

The main objective of this research work is to increase the physical, mechanical properties and durability properties of recycled aggregate concrete (RAC), but the objective listed below are of great importance.

1. Investigate the specific gravity, and water absorption rate of aggregate i.e., sand, recycled coarse aggregates (RCA), natural coarse aggregate (NCA) and then make comparison among them.
2. Investigate the porosity, specific gravity, and water absorption rate of the treated recycled coarse aggregate.
3. Make comparison in term of compressive and tensile strengths among treated and untreated recycled aggregate concrete and conventional concrete.
4. Compare the drying shrinkage and water absorption rate of hardened treated and untreated recycled aggregate concrete.
5. Observe the trend of the slump values.

1.4 Research significance

This research study outlines the following key significances.

- It will give adequate insight about RCA and encourage its usage to prevent depletion of NCA.
- The awareness and the usage of RCA will drastically reduce the pressure of C&D waste on landfills and significantly improve the environment quality.

1.5 Thesis structure

This thesis outlines 7 chapters as presented below:

Chapter one Introduction

This chapter introduces the background of study, aim and objectives of the thesis and significance of the research etc.

Chapter two Literature Review

This chapter highlights provides detailed understanding about construction and demolition waste, environmental impacts of C&D waste, recycled aggregate concrete, treatment of RCA with nanotechnology and mechanical properties of RAC.

Chapter three Methodology

The chapter describes the methodology of the research work. It gives description of all the experiments performed, source of materials, the equipment used, the method the experiments were carried out and the test matrix used for concreting.

Chapter four Result

This section focuses on the detailed experimental results. The mechanical tests such as compressive and splitting tensile strength tests result are presented. The durability properties of hardened concrete which is presented by drying shrinkage and water absorption results are presented in this chapter

Chapter five Discussion

The fifth chapter is the discussion part. This part focuses on the detailed explanation of the results presented in chapter and comparison of these results with previous studies and standards.

Chapter 6 Conclusion

This chapter will provide a detailed summary of all the findings

Chapter 7 Future work

This chapter will provide the identified research possibilities.

Chapter 2: LITERATURE REVIEW

2.1 Construction and demolition (C&D) waste

Construction and demolition (C&D) are waste generated from all economic activities that involves construction, maintenance and demolition of civil and public works(Gálvez-Martos et al. 2018). C&D waste consists of plastics, metals, concrete and rubble, clean drywall, roofing and wood(MassDEP 2008). Concrete waste is accountable for 20.2 to 45.3 percent of the total composition(MassDEP 2008). Globally, the annual construction and demolition waste was estimated to about 3 billion tons (Akhtar & Sarmah 2018).China ranking the first C&D waste generator in the world approximately generated 1.13 billion tons of C&D in 2014(Menegaki & Damigos 2018). In addition, between the years 2018-2019,Australia generated 27 million tons of C&D waste and it is accountable for 44% of the total waste generated in the country(Picklin et al. 2020).

2.2 Problems associated with C&D wastes

There are various problems associated with the disposal of the C&D waste. Some of which are occupying landfills by taking up land resources and polluting the environment(Luo et al. 2019). Also, the construction industry is accountable for the largest emission of CO2 into the atmosphere (De Brito 2013). According to statistical data, C&D wastes accounts for 10-30% of waste being received at the landfill. About 33% of waste deposited in the landfill in the United States are mainly from construction and demolition activities, also 65% for Hong Kong,35% for Canada, 50% for the United Kingdom and 20-30 % for Australia(Polat et al. 2017). The excessive C&D waste has led to increase in the cost of buying lands and increase in the cost of dumping at landfills(Behera et al. 2014).

2.3 Solutions to C&D waste

Concrete is a material which is made up water, binding material such as cement, aggregates, and admixtures. These aggregates play a key role in concrete as it occupies 60-70% volume of the total concrete(Behera et al. 2014). The aggregates are basically the natural aggregates and sand. The natural aggregates (NA) are also known as the coarse aggregates while the sand is known as the fine aggregates. The increase in the usage of these aggregates is expected to double as years goes by thereby leading to more usage of natural resources and indirectly increase in the construction and demolition waste(Behera et al. 2014).Also,(Silva, de Brito & Dhir 2019) reviewed that the global need for aggregates is expected to rise from 45 billion tons in 2017 to 66 billion tonnes by 2025.

The process of converting the concrete waste into recycled coarse aggregate is considered the best action to address C& D waste problems and also saves the aggregates from depletion(Luo et al. 2019).The recycled aggregates obtained from construction and demolition wastes can boost the global economy by reducing the usage of the natural resources such as the natural aggregates(Pourkhorshidi et al. 2020). (Ohemeng & Ekolu 2020) reported that the benefits of producing recycled coarse aggregate from C&D waste was positive with value of 22,334,116USD,while that of natural coarse aggregates(NCA) had a negative value of -31,841,109USD. (Ohemeng & Ekolu 2020) reported that the use of recycled coarse aggregate will reduce exploitation of quarries and reduction of greenhouse gases associated with mining. The use of recycled coarse aggregates provides the opportunity to achieve greater sustainability through the total or partial replacement of NA in concrete production (Abdollahnejad et al. 2019). The Figure 1 shows recycling process of C&D waste.

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Figure 1. Recycling of C&D waste process (Behera et al. 2014)

2.4 Problems associated with recycled coarse aggregate

Different studies have revealed that the use of recycled coarse aggregate over natural coarse aggregate for production of concrete usually offer lesser strength, material durability and structural performances(Luo et al. 2019).(Yehia et al. 2015) reported that the water absorption rate, aggregate size, porosity specific gravity, strength of aggregates, abrasion resistances are major properties that limits the use of recycled coarse aggregate for concrete production. The water absorption capacity of RCA is about 12%, and it is 2-3 times greater than that of the natural coarse aggregates(Poon, Shui & Lam 2004).Their study also revealed that the crushed granites (NCA) used in Hong Kong possess density ranging from 2600-2650kg/m^3 and water absorption capacity of 1% whereas the RCA has density varying from 2200-2400kg/m^3 and water absorption rate ranging from 5 to 15**%.** (Behera et al. 2014) stated that the water absorption capacity of RCA greater than 7% is not suitable for concrete production. It is to be noted that the variation in water absorption capacity and density is due to the presence of attached old mortar on RA (Butler, West & Tighe 2011). (Xiao, Li & Poon 2012) revealed that recycled coarse aggregate are more porous than natural coarse aggregate. Their study revealed that the porosity and crushing index of RCA is approximately 23% and 9.2-23.1% respectively. (Butler, West & Tighe 2011) investigated that NCA has higher abrasion resistance than the RCA. It was shown that NCA had 21 % higher abrasion resistance than the RCA and this is also due to the attached old mortar on RCA. The Figure 2 shows the production of recycled coarse aggregate from C&D waste.

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Figure 2. Recycled coarse aggregate production (Xiao 2018)

2.5 Recycled aggregate concrete (RAC)

(Luo et al. 2019) revealed that the strength and durability properties of recycled aggregate concrete are a bit lower than the natural aggregate concrete, and this may be due to the weak nature of the recycled coarse aggregate. (Liu, Xiao & Sun 2011) revealed that RAC is a composite material made of old attached mortar, new attached mortar, and the interfacial transition zone. The study further explained that the ITZ are divided into old and new ITZ. The old ITZ is formed between the original natural aggregate and the old cement paste matrix while the new ITZ zone is formed between the RCA and the new cement paste matrix. The new ITZ created is the weak point in concrete and it greatly affect the mechanical properties of the recycled aggregate concrete(Diamond & Huang 2001).Many studies have reviewed that the concentration of RCA influence the compressive strength of concrete(Xiao et al. 2012). The study explained that the higher the RCA content in a concrete mix, the lower the compressive strength of the concrete and vice versa. The Figure 3 shows the old and new interfacial transition zone in RAC.

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Figure 3. Diagram of old and new ITZ in RAC (Diamond & Huang 2001).

2.6 Improvement of recycled aggregate concrete

Many researchers have performed different studies on how to improve the mechanical properties of recycled aggregate concrete. Some studies focused on using nanotechnology to treat RCA in order to perform satisfactory in concrete (Sharma & Arora 2018),while some used acidic solution as a form of treatment to RCA for better performances(Ismail & Ramli 2014a). Different studies on the improvement of RAC will be reviewed in this section.

(Mukharjee & Barai 2014) studied the influence of nano-silica on the properties of recycled aggregate concrete. In this studies, nano silica was incorporated into a concrete mix containing 100% recycled coarse aggregate and another concrete mix containing natural coarse aggregate and recycled coarse aggregate with varying cement proportion. It was observed that the influence of the nano silica helped in the increment of the mechanical properties of the RCA and NCA. At 7 days, the compressive strength of RAC was increased from 30.3MPa for the untreated mix, to 34.13MPa for the mix with the addition of 3% nano silica. In addition, at 28days, the compressive strength of NAC was increased by 22% against the control mix with the increment of nano silica. The result above is similar to (Wang et al. 2020) that used nano silica as treatment to RAC. In here, the RCA was soaked in a solution containing nano silica before incorporating into concrete. Split-Hopkinson bar (SHPB) was conducted to analyse both the recycled coarse aggregate and the nano silica modified aggregate. 2% nano silica modification on the RCA improved its mechanical properties. The apparent density was increased by 1.6% and the water absorption was deceased by 21.46%. In addition, the compressive strength was improved by the nano silica modification, however there was no effect on the flexural strength of RAC. The compressive strength of untreated RAC was 32.4MPa while the nano modified RAC was seen to have an increased strength of 36.46MPa.

Table 1 presents the compressive strength of concrete made up of 30% RAC. (Balasubramaniam, Karthick & Arun 2021) studied the partial replacement of NCA with RCA with the addition of reduced graphene oxide to the cement paste for the reinforcement of the mixture. 30% of RCA was introduced to replace NCA with cement having 0%,0.3%,0.6%, and 0.9% of reduced graphene oxide added respectively. From the mechanical properties of the concrete, it was obtained that the concrete made of RCA with reduced graphene oxide had higher compressive and tensile strength than that without reduced graphene oxide. At 28days,0.6% of reduced graphene oxide has optimum compressive and tensile strength at 31MPa and 4.02MPa.Similar result was obtained from(Fang et al. 2017) that investigated the effect graphene oxide have on the mechanical properties of recycled mortar. The inclusion of graphene oxide increased the mechanical properties of the recycled mortar. For flexural and compressive strength test, it was found that recycled mortar containing 0.2% of graphene oxide at 14 and 28days exhibited 22% and 41.3% ,16.4% and 16.2% increase in strength over the ones without graphene oxide.

Table 1. Compressive strength of reinforced RAC containing 30% of RCA (Balasubramaniam, Karthick & Arun 2021).

% of rGo with RCA concrete mix	Compressive strength in N/mm^2		
	7 days	14 days	28 days
0%	16	20	25
0.3%	20	24	28
0.6%	25	30	34
0.9%	22	26	31

(Ismail & Ramli 2014a) investigated the influence of surface treatment of recycled aggregate concrete with nanomaterial and a chemical compound. The RCA was first treated with calcium metasilicate before immersing into a solution containing nano-silica at different concentrations. It was concluded that the concrete made with treated RCA had higher density than the untreated RCA. The compressive strength of the concrete made with treated RCA was improved and exhibited strength higher than the untreated RCA. At 28 days, it was obtained that mix CM10 had the highest compressive strength(56.18MPa) over the control untreated mix(47MPa). The addition of calcium metasilicate also improved the workability of the treated RAC.

Figure 4 below shows the coating procedure of recycled coarse aggregate with dispersant. (Ryou & Lee 2014) studied the characterisation of RCA by coating techniques. The study was based on the application of polycarboxylate dispersant on the surface of RCA to form a film on it surface and so improving it mechanical properties. It was finalised that the coating of the polycarboxylate on the surface of RCA helped in the increase in compressive and tensile strength. At 28 days, treated RCA with 75% coating produced the maximum compressive strength of 31.9MPa as against the control sample which was 27. 1MPa.Generally, it was stated that this approach had a slight improvement in the mechanical property of RCA.

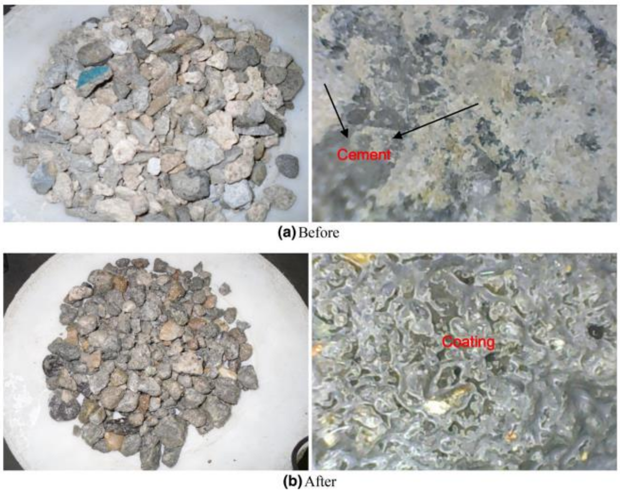

Figure 4. Coating procedure with polycarboxylate dispersant (Ryou & Lee 2014)

Figure 5 below shows the ultrasonic velocities at different curing days.(Devi & Khan 2020) investigated the mechanical properties and durability nature of graphene reinforced recycled aggregate concrete. The study made use of 100% of RCA as total replacement for NCA with the addition of graphene oxide (GO) and graphene oxide ball milled (GObm). In addition, a control mix of 100% NCA with 70% ordinary Portland cement (OPC) and 30% fly ash was produced with remaining mix containing 100% of RCA with 0%,0.05% and 0.1% GO and GObm by weight of the binder. It was observed that the addition of these nanomaterial influenced the mechanical properties such as the compressive strength, electrical sorptivity and ultrasonic pulse velocity. For sorptivity, it was observed that the mix with 100% RCA without treatment produced the least sorptivity in comparison with other mixes. The mix with 0.1% of GObm added was seen to have a better UP velocity over the control mix, with velocity ranging from 3.457-4.137km/s. Lastly for the compressive strength, it was seen that 0.1% of G0 increased the compressive strength of mix containing 100% RCA by 50%.

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Figure 5. Ultrasonic pulse velocity for different mixes (Devi & Khan 2020).

The Figure 6 below describes the spraying method used for RCA. (Ismail & Ramli 2014b) studied the mechanical strength and drying shrinkage properties of concrete made from recycled coarse aggregate. The study experimented two treatments for RCA. The first treatment was with (HCL) and the second was impregnation of the RCA with calcium metasilicate which serves as a means of coating its surface with the chemical. The combination of the treatment was effective by modifying RCA surface and improvement of its properties. It was seen that the water absorption capacity of the RCA was reduced with the addition of the chemicals from 4.44% to 3.48%. At 28,90 and 180days, the compressive strength treated RAC was increased by 96%,99% and 98% which is close to the strength of the control concrete. For the durability properties of the RAC, it was reported that the drying shrinkage of concrete was reduced with mix treated RCA.(Li, L et al. 2021) also used nano silica in the treatment of recycled coarse aggregate but spraying techniques was employed. The techniques used included the pre-spraying plus drying technique-spraying without air drying and pre-soaking with air-drying inclusion. It was reported that the pre-spraying nano silica was the best approach and produced good mechanical and durability properties of RAC. Compressive strength of RAC treated with nano silica at 1%,3% and 5% exhibited compressive strengths at 9.5%,11.2% and 6.1% higher than the untreated RAC. Both studies reviewed that nano silica was effective in treating RAC.

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Figure 6. Diagram of Recycled coarse aggregate (RCA) before(a) and after(b) using the NS pre-spraying plus air-drying technique (Li, L et al. 2021).

(Shaikh & Odoh 2014) examined the effect of nano silica on recycled aggregate concrete. The study is investigated by having a control mix which has natural coarse aggregates without nano silica added while the other mixes contain nano silica at varying ratios with partial replacement of natural coarse aggregate with recycled aggregates. In terms of the mechanical properties of the reinforced recycled aggregate concrete, it was shown that the mix containing 25% of RCA and 1% and 2% of NS had its compressive strength increased. It was observed that mix with 2% of NS performed slightly better than the mix with 1% of NS. At 28 and 56 days, the reinforcement of RCA with NS yielded 70- 90% increase in compressive strength. In addition, the addition of NS also had effect on the tensile strength. At 28 days, the mix containing 50 % of RCA and 2% of NS performed than the mix with 25% of RCA. It was also seen that the addition of NS decreases the sorptivity of RAC.

(Kumar & Kumar 2021) studied the influence of graphene oxide on the recycled aggregate concrete. The research worked on partial replacement of natural coarse aggregates with 0,10,20 and 30 % of recycled coarse aggregates with the addition of graphene oxide to the cement at varying percentages. Mechanical tests such as compressive, tensile, and flexural strength tests were performed on the treated and untreated mixes. It was reported that the addition of the nanomaterial improved the strength of the concrete. The addition of 0.05% of graphene oxide increases the compressive, tensile, and flexural strengths by 72%,73% and 70% respectively.

The mix containing 30% of RCA and 0.05% of graphene oxide produced the maximum compressive strength of 42. 08MPa.The durability properties of the recycled aggregate concrete was not reported in this study.

(Yu & Wu 2020) investigated the use of graphene oxide (GO) to improve the mechanical properties of ultra-high-performance concrete (UHPC) made with recycled fine aggregate. In this study, recycled fine aggregate was used to replaced natural river sand in the production of ultra-high-performance concrete. It was found that concrete made with recycled fine recycled aggregate had better mechanical properties than those made with natural river sand. The treatment with graphene oxide increased the compressive and elastic modulus of UHPC by 2.04%-16.04% and 5.85%-23.40% respectively. It was also seen that the durability properties of the concrete were improved by the incorporation of GO. The drying shrinkage rose from 1.33%-6.72%. The porosity of the mix was also reduced by the addition of graphene oxide. The chloride penetration and freezing thawing resistances of UHPC was improved with the addition of GO.

(Song et al. 2021) studied the interfacial properties of recycled aggregate concrete (RAC) reinforced with Nano silica (Nano-SiO2) and carbon nanotubes. The tensile and shear strengths test was conducted on both the old and new attached mortars for the microstructural studies. It was seen that the shear and tensile strength of recycled aggregate concrete was improved by thew addition of these materials. Carbon nanotubes produced the maximum shear and tensile strength by an increase of 51% and 53% respectively.

(Younis & Mustafa 2018) examined the feasibility of SiO2 in the improvement of recycled aggregate concrete. Mixes of 50 % and 100 % of recycled coarse aggregate (RCA) were reinforced with dosages of SiO2 at 0.4%,0.8% and 1.2% by mass of cement and control mix which is made of natural aggregates was made available for comparisons. The compressive strength, tensile strength, water absorption rate and microstructure of RAC were tested. It was found that the compressive strength of the untreated RAC were lower than the control mix. With the addition of nanoparticles to the mix having 50% RCA at different dosages at 0.4%,0.8%, and 1.2% have an increased compressive strength by 10%,18% and 24%. In addition, the mix containing 100% of RCA have an increased compressive strength by 6%,13% and 16% respectively. The splitting tensile strength of the RAC was also influenced with the incorporation of SiO2. It was seen that the splitting tensile strength of mix containing 100% of RCA rose to about 8%. Regarding the durability properties of the RAC, it was established that the water absorption of the RAC was reduced with the addition of SiO2. 0.4% of nanoparticles produced no significant effect on the water absorption but 0.8% of nanoparticles yielded a water absorption capacity reduced by 10% and 11% for mixes containing 50% and 100% RCA.

Figure 7 shows the treatment of RCA with HCL and Table 2 shows the properties of RCA upon treatment. (Abhiram & Saravanakumar 2015) studied the effect of hydrochloric acid (HCL) on recycled coarse aggregates. The paper experimented soaking recycled coarse aggregate in a solution containing 0.1M HCL for 24 hrs before incorporating into concrete. It was seen that the mechanical properties of recycled coarse aggregate were improved by pre-soaking technique. In addition, the properties of hardened concrete were also improved. At 28days, the treated RCA produced higher compressive strength than the untreated RAC. It was also found that the compressive strength of the treated RAC was 19% lesser than that of the control mix containing natural aggregate

Figure 7. Recycled coarse aggregate before and after treatment with HCL(Abhiram & Saravanakumar 2015)

Table 2. Properties of treated recycled coarse aggregate(Abhiram & Saravanakumar 2015)

S/N	Property	NA	RA	RA(HCL)
1	Specific Gravity	2.67	2.47	2.49
2	Water absorption (%)	1.56	6.48	5.08
3	Density Kg/m3	1635.5	1392.59	1422.22

The literature reviews above showed that recycled coarse aggregate can be treated with nanomaterial to improve the strength of RAC but none has shown a greater improvement. Also, the feasibility of the production of large scale treated RCA have not been considered. Majority of the methods described above can only be practicable in a small-scale production of concrete. However, the use of pristine graphene for the research work is advantageous over other methods because the process of treatment used with pristine graphene can allow mass treatment of RCA. In addition, as clearly stated in the objectives of the research, the strength offered by pristine graphene is much greater than any other nanomaterial. This turns out that much strength will be expected in the use of pristine graphene as reinforcement to recycled coarse aggregate over other nanomaterials.

Chapter 3: RESEARCH METHODOLOGY

3.1 Materials

The materials used for this research are the natural coarse aggregate, sand recycled coarse aggregate and pristine graphene. The natural coarse aggregate was obtained from McLaren Vale Quarry in South Australia. The natural sand with a size of 1mm was sourced from the Price Pit, South Australia and the pristine graphene was shipped from China. The experimental processes, mixing and production of recycled and natural aggregate concrete was performed at the Concrete and Materials Laboratory of Flinders University, South Australia. Figure 8 shows the particle size distribution of aggregates

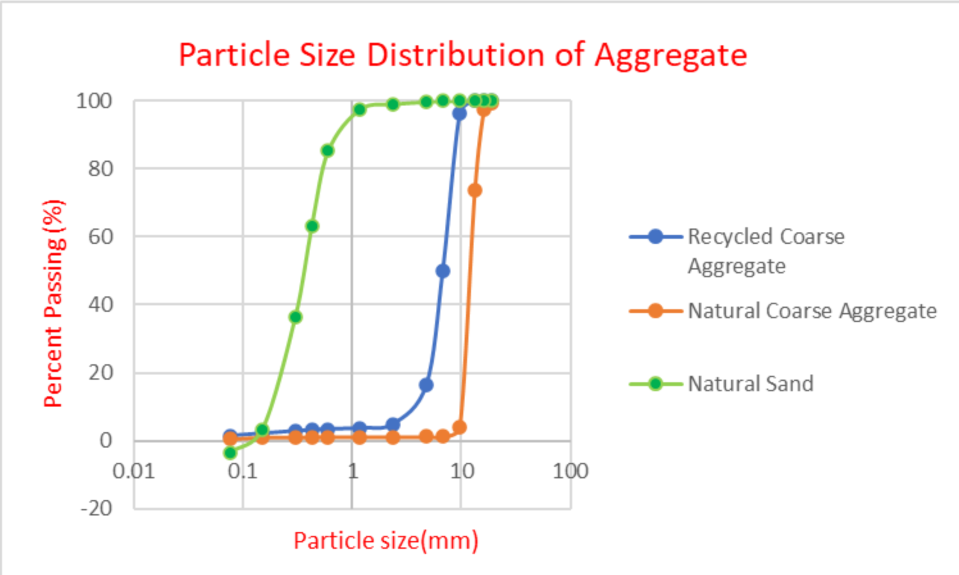

Figure 8.Sieve analysis result for natural sand, RCA and NCA

The physical properties of recycled coarse aggregate, natural coarse aggregate and sand are shown in Table 3.

Table 3. Properties of NCA, RCA and sand

Aggregate Type	Maximum size (mm)	Specific Gravity	Water absorption(%)
Natural Coarse Aggregate	20	3.14	1
Recycled Coarse Aggregate	10	2.31	8.6
Sand	19	2.55	0.63

3.2 Experimental Procedure

Classification Test

The classification tests are the preliminary test performed on the aggregates. These tests include sieve analysis test, particle density, water absorption test, porosity test etc. These tests were performed to characterise the physical properties of sand, natural aggregate and recycled coarse aggregates.

Sieve Analysis

This test was performed in accordance with the specifications provided in AS 1152-1993(Standard 1993). The importance of this test was to enable to know the particles size distribution of aggregates. For this research work, the sizes of sieve employed were 19mm,16mm,13.2mm,9.6mm,6,7mm,4.75mm,2.36mm,1.18mm,0.6mm,0.425mm,0.3mm,0.15mm,0.075mm and pan. The test was performed on sand, recycled coarse aggregate and natural aggregate at Flinders College of Science and Engineering, Civil Engineering Laboratory

Particle density and water absorption of aggregates

The particle density and water absorption of fine aggregate was conducted in accordance with the specification provided in AS 1141.5-2000, particle density and water absorption of fine aggregates. The natural aggregate and recycled coarse aggregate water absorption and specific gravity was performed with the requirement provided in AS1141.5-2000(Standards 2000). The importance of the water absorption test was to determine the amount of water being absorbed by the aggregates. As reviewed from different literature, an aggregate that absorbs too much water has a bad mechanical property and it is not fit for concrete production. This test helped in the differentiation of natural aggregates and recycled coarse aggregates based on the water absorption capacity.

Treatment of recycled coarse aggregate with pristine graphene

The treatment of recycled coarse aggregate with pristine graphene involves different stages. They are the heating, mixing/stirring and the soaking stage The method used in treatment of this aggregate was adapted from the previous studies (Balasubramaniam, Karthick & Arun 2021; Devi & Khan 2020)

Heating process

In this phase, the recycled coarse aggregate was placed in thermostatic oven for up to 48 hours at a temperature of 107°C.This process was performed in order to dry up the aggregates particle making it more possible to expose the pore spaces to be filled up with pristine graphene solution. The drying process is shown in Figure 9.

Figure 9.Drying of the RCA in an oven

Mixing/stirring and soaking process

This stage involves mixing the graphene solution in water with the aid of a stirrer to establish a perfect mix of graphene solution and water. The stirring and mixing were done for 30 minutes, and 4 dosages of graphene solution were prepared based on volume of water. They dosages used were 0.1%,0.2%,0.3% and 0.5% respectively. The next step was soaking of the RCA into different dosages of graphene for 24 hours. The main reason for doing this is for the graphene solution to react with the recycled coarse aggregate by reinforcing the primary adhered mortar on the surface of the aggregates. These attached mortars are from the original aggregate and if it is incorporated into concrete without reinforcement or treatment, it brings in another zone called the interface transition. This zone brings the weak point of the concrete, so there is a necessity to treat the recycled coarse aggregate with graphene. The specific gravity and water absorption rate was performed on one of the treated recycled aggregates. Upon soaking of the RCA, the saturated RCA was collected and ready to be incorporated into concrete. The stirring, mixing and soaking procedure is shown in Figures 10 and 11.

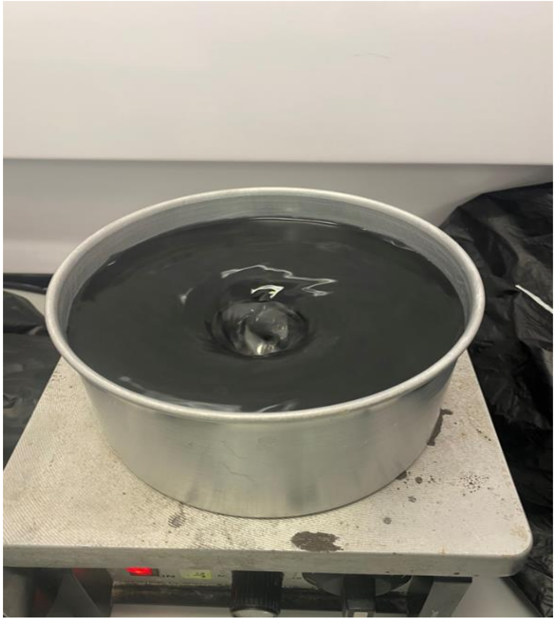

Figure 10.Stirring and mixing of graphene particles with water

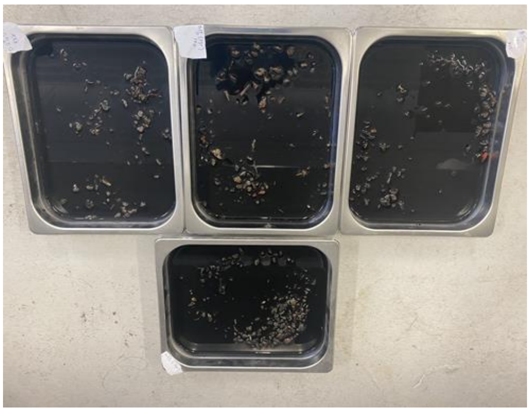

Figure 11.Soaking of RCA into different dosages of graphene

3.3 Test Specimens

There were six batches of concrete prepared and 84 specimens in total. The first mix which is the control mix is made up 100% natural aggregate concrete. The second mix is made up of 50% of natural coarse aggregate and 50% of recycled coarse aggregate. The third to sixth mixes were made up of 50% natural coarse aggregate and 50% recycled coarse aggregate with different dosages of graphene. Different tests such as the workability (slump test), compressive strength, splitting tensile strength, drying shrinkage and water absorption were performed on the fresh and hardened concrete. For the compressive and splitting tensile strength tests, the cylinder was employed. The cylinder has the dimension of 100 mm diameter and 200 mm in height. The prism with the dimension 75x75x285mm was used to measure the drying shrinkage of the hardened concrete and the water absorption was measured by cutting the mould made with the cylinder.

3.4 Mix design and concrete preparation

The table 3 shows the percentages of each constituent of the concrete that were mixed. The mixing method employed was in accordance with AS 1012.2:2014(Standard 2014a). The total mixing time was 14 mins. The fine and coarse aggregate were first added and mixed for two minutes, and the other concrete components were added afterwards and then mixed for another two minutes. After the mixing, the slump was measured, and the concrete sample were placed in cylinders and prism to vibrate for proper placement of the concrete. The specimen was left in the cylinder and prism for 24 hours before demolding. Upon demolding, as seen in Table 4, sample were labelled N100%R0%P0%, N50%R50%P0%, N50%R50%P0.1%, N50%R50%P0.2%, N50%R50%P0.3% and N50%R50%P0.5%. The N signifies the natural coarse aggregate, R, the recycled aggregate and P, the pristine graphene. The next step was placing the demolded specimen in a curing tank and the procedure for curing was followed according to the guideline specified in AS102.8.1:2014(Standard 2014c). Table 4 shows the test matrix used and Figure 13 shows the measurement of workability of the concrete specimen.

Table 4.Test matrix of mix

Mix ID	Cement	Sand	NCA	RCA	RCA-PRG	PRG Dosage	Water
N100R0P0%	100%	100%	100%	0%	0%	0%	100%
N50R50P0%	100%	100%	50%	50%	0%	0%	100%
N50R50P0.1%	100%	100%	50%	0%	50%	0.10%	100%
N50R50P0.2%	100%	100%	50%	0%	50%	0.20%	100%
N50R50P0.3%	100%	100%	50%	0%	50%	0.30%	100%
N50R50P0.5%	100%	100%	50%	0%	50%	0.50%	100%

3.5 Testing

The mechanical properties such as the compressive and tensile strength of the recycled and natural coarse aggregates concrete were measured after curing for 7 and 28days. The compressive and splitting tensile strength were performed in accordance with the specification provided in AS 1019.9:2014(Standard 2014b),AS 1012.10-2000(Standard 2000) with the aid of a universal testing machine. There were three repetitions of both tensile and compressive strength test on each mix. The workability of fresh concrete which was assessed by the slump test was performed in accordance with AS 1012.3.1:2014 (Standard 2014d).The durability tests such as the drying shrinkage and water absorption of hardened concrete were carried out with specifications provided in AS 1012.13:2015(Standard 2015) and AS 1012.21-

1999(Standard 1999). The drying shrinkage which is the change in volume of concrete can result in cracking of the concrete and thereby exposing the reinforcing bars to corrosion. According to the AS 1012.13:2015(Standard 2015) ,the drying shrinkage of concrete is recommended to be measured at 7,14,21,28 and 56 days. However, the drying shrinkage for this research was only able to be measured up to 28 days due to time constraints. The drying shrinkage of a hardened concrete was measured with a length comparator which measures lengths ranging from 290mm to 300mm with a precision of 0. 001mm.The methods used in determination of the mechanical properties of fresh and hardened concrete is summarised in Table 5.

Table 5 Methods and procedures used in determination of fresh and hardened concrete

Test and Procedures	Method
Slump test	AS 1012.3.1:2014(Standard 2014d)
Compressive strength	AS 1019.9:2014 (Standard 2014b)
Splitting tensile strength	AS 1012.10-2000(Standard 2000)
Drying shrinkage	AS 1012.13:2015(Standard 2015)
Curing	AS102.8.1:2014(Standard 2014a)
Mixing	AS 1012.2:2014(Standard 2014a)

Chapter 4: EXPERIMENTAL RESULTS

This chapter discusses the result of the property of treated recycled coarse aggregate, workability of freshly prepared concrete, mechanical properties of hardened concrete and their durability

4.1 Properties of treated recycled coarse aggregate

Figure 12 shows the specific and water absorption of treated RCA.Upon treatment with the pristine graphene, the specific gravity and water absorption test was performed on the treated recycled coarse aggregate. The water absorption of untreated RCA was higher as seen in Table 3. The treatment was able to reduce the water absorption by 33% as shown in Figure 12. Also, the specific gravity was affected with the treatment with pristine graphene. The specific gravity of the treated RCA was increased to 2.58 and that amount to about 12% increase.

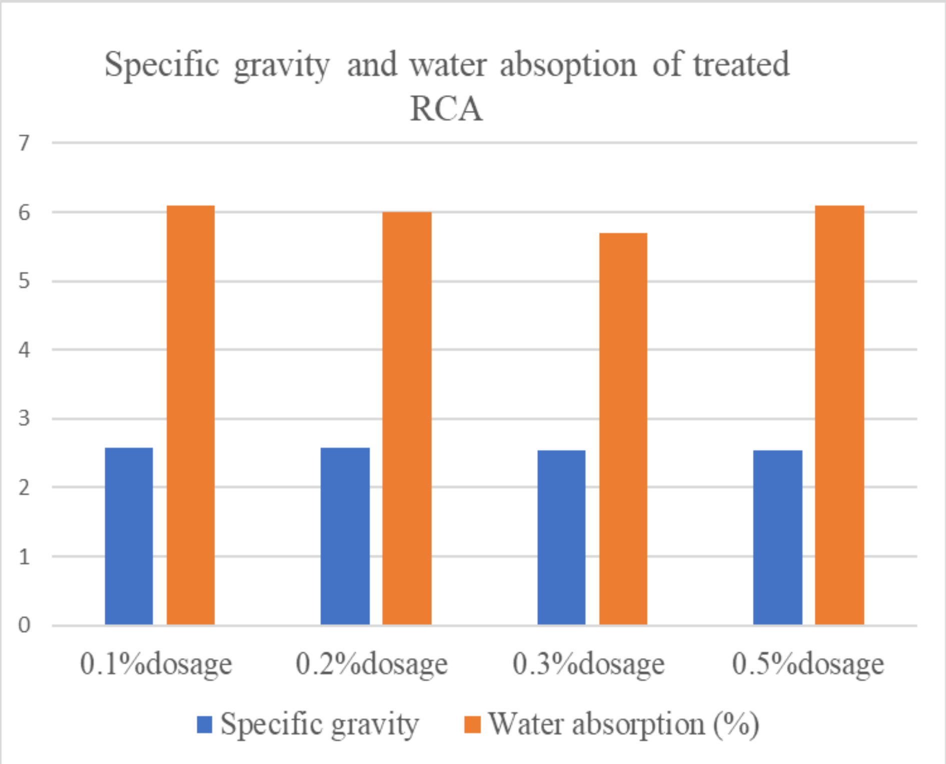

Figure 12.Specific gravity and water absorption rate of treated RCA

4.2 Workability of fresh concrete

Figure 13 depicts the slump values for NAC and RAC mixes. As seen from the slump test in Figure 13, the slump of the treated RAC was reducing with increase in the graphene dosage. The mix N50R50P0.5% had the least slump value of 45mm and mixes N50R50P0.1% and N50R50P0.2% had the highest slump value.

Figure 13. The slump value for the NAC and RAC mixes

4.3 Mechanical properties of hardened concrete

4.3.1 Compressive strength

Table 5 shows the compressive strength of the RAC and NAC at 7 and 28 days. It can be observed that the control mix N100R0P0% has the highest compressive strength at both 7 and 28days. It can also be seen that the addition of graphene to RAC had influence on its compressive strength. At 28 days, treated mix N50R50P0.2% produced 60.74MPa which is 19% higher than the untreated mix N50R50P0%.

Figure 14.Compressive strength test

Table 6.Compressive strength of RAC and NAC at 7 and 28 days

Compressive strength (MPa)		
Mix	**7 days**	**28 days**
N50R50P0.1%	44	56.11
N50R50P0.2%	48.49	60.74
N50R50P0.3%	46.12	52.27
N50R50P0.5%	45.09	54.13
N100R0P0%	48.93	62.41
N50R50P0%	40.05	51.04

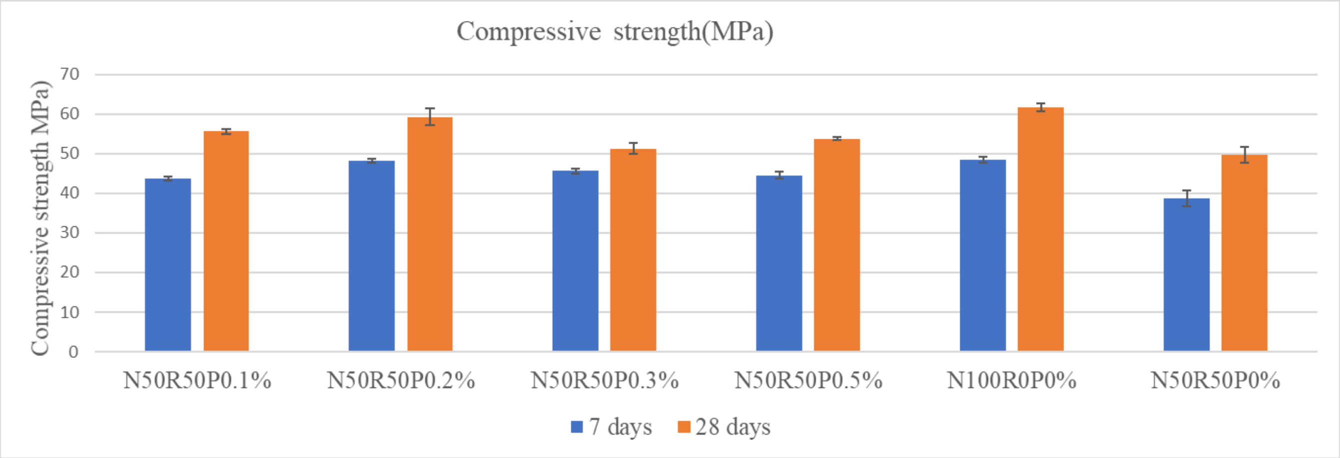

Figure 15. The compressive strength of RAC and NAC at 7 and 28 days

In addition, it can be deducted that mix N50R50P0.2% is the optimum dosage of graphene because it has the highest compressive strength at both 7 and 28 days. The Figure 16 shows the optimum dosage of pristine graphene for RAC treatment.

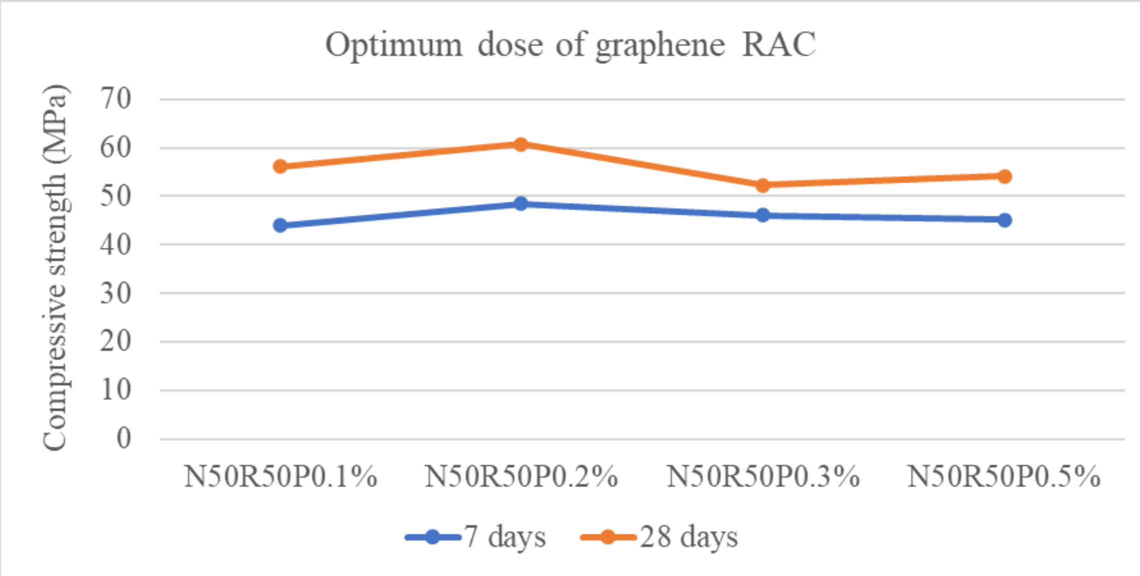

Figure 16. Optimum graphene dose at 7 and 28 days

4.3.2 Splitting tensile strength

Table 7 shows the splitting tensile strength of the RAC and NAC.It can be obtained that untreated RAC has more strength than the treated RAC. N50R50P0% which is the untreated RAC has splitting tensile strength of 4.47MPa which is 2.9% more than the treated RAC and 12% less than the control mix N100R0P0%. The difference between the splitting tensile strength of treated RAC and untreated RAC is not obvious.

Figure 17.Splitting tensile strength test

Table 7. Splitting tensile strength of RAC, treated RAC and NAC

Splitting tensile strength(MPa)		
Mix	7days	28days
N50R50P0.1%	3.85	4.07
N50R50P0.2%	4.19	4.34
N50R50P0.3%	4.12	4.28
N50R50P0.5%	3.52	4.01
N100R0P0%	3.94	5.09
N50R50P0%	3.52	4.47

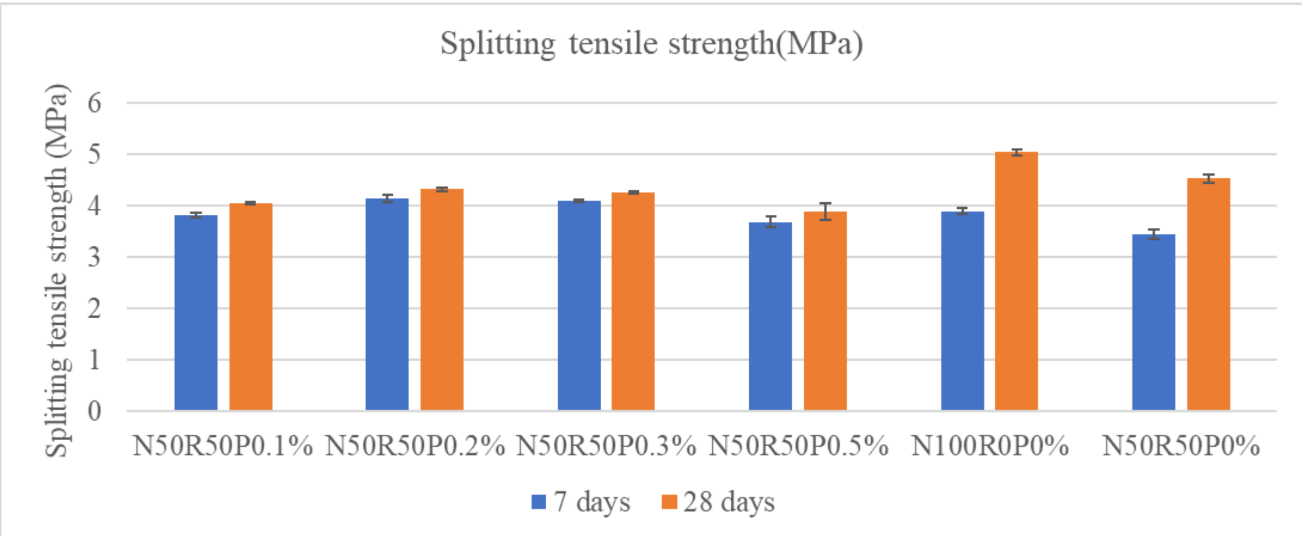

Figure 18. Splitting tensile strength chart for RAC, treated RAC and NAC

4.3.3 Drying shrinkage

Figure 19 shows the drying shrinkage of the NAC and RAC. The drying shrinkage of mix N50R50P0% which is untreated RAC exhibited the highest shrinkage of about 800 micro strains. Figure 18 shows the shrinkage trend of RAC, treated RAC and NAC.

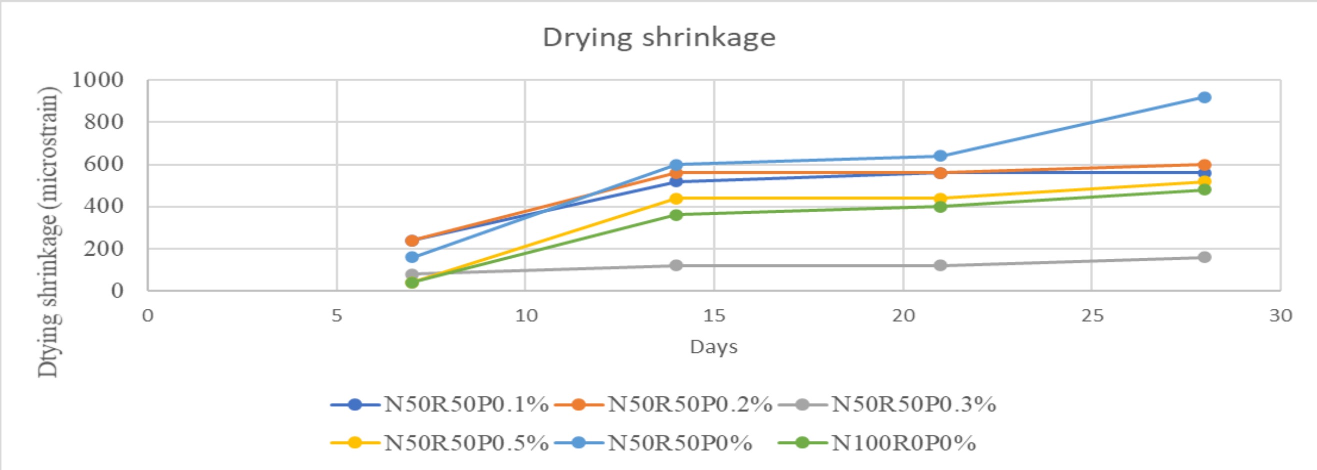

Figure 19. Drying shrinkage of RAC and NAC

4.3.4 Water absorption of hardened concrete

Figure 20 shows the water absorption of hardened concrete. It can be suggested that the addition of pristine graphene had effect on mix N50R50P0.1% by reducing it porosity and improving it microstructures. The water absorption rate of N50R50P0.1% which one of the treated RAC was 2.69% as against the untreated RAC that exhibited 4.11%. The result obtained here is similar to the findings in (Li, W et al. 2017)where nano silica was used as a reinforcing material to recycled aggregate concrete.

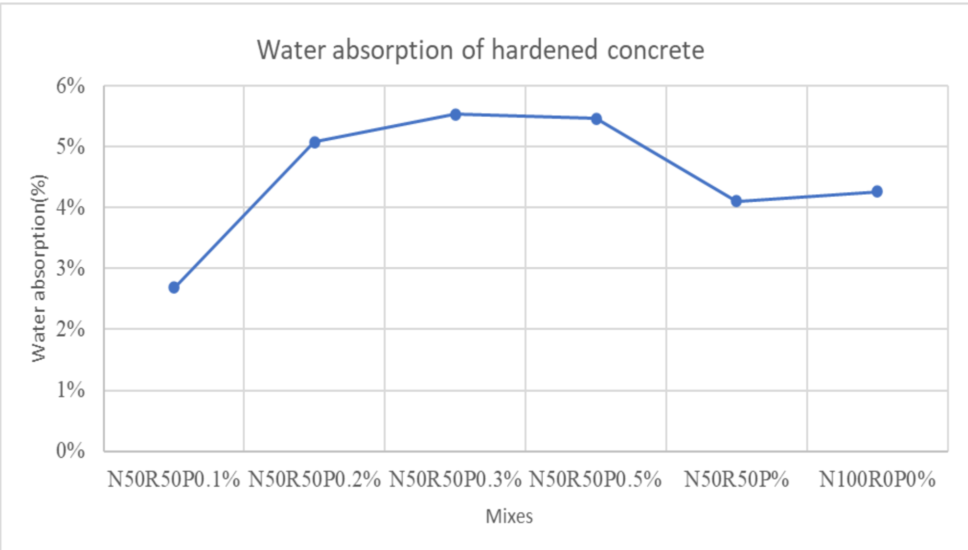

Figure 20.The water absorption of NAC, RAC and treated RAC

Chapter 5: DISCUSSION

5.1 Specific gravity and water absorption of treated RCA.

It was seen that the water absorption and specific gravity of treated RCA was improved by the addition of pristine graphene. The treatment was able to reduce the water absorption rate by 33%. In addition, the specific gravity was also increased by graphene addition. It can be concluded that the graphene solution helped in filling up the pore’s spaces of recycled coarse aggregates and simultaneously increasing its specific gravity.

5.2 Slump of concrete

The figure 13 presented the slump of the fresh prepared concrete and the mixes N50R50P0.3% and N50R50P0.5% exhibited the least slump while the untreated mix and the control mix have similar slump values. It can be concluded that the addition of pristine graphene dosage led to the decrease in the slump values of freshly prepared concrete by reinforcing the RCA pore spaces and bringing adequate compaction forces among the aggregates. The findings here is in support with the results obtained in (Alqarni et al. 2021).It can also be concluded that the slump value is within acceptable range as specified in AS 3600:2018(Standards 2018).

5.3 Compressive strength of NAC, RAC and treated RAC

The compressive strength of RAC, treated RAC and NAC as presented in Table 6, it can be obtained that the treatment of pristine graphene helped in the increase of compressive strength of RAC. The maximum strength was achieved with mix N50R50P0.2% at both 7 and 28 days. The higher compressive strength was believed to be as a result of the graphene having the ability to reinforce and fill the pore space on the attached old mortar on the RCA. The old, attached mortar is believed to be the weak zone of the concrete. The filling of the pore spaces of the RCA gives it more density and reduce porosity. As seen in Figure 16, it was obtained that RAC containing 0.2% of pristine graphene produced the highest compressive strength. This is because when nanomaterials of different dosages are added to RAC, they reach a high level, and they tend to agglomerate with each other as a result of higher surface energy (Luo et al. 2019). This simply means that dosage N50R50P0.5% which is the highest dosage agglomerated and was not able to attract all the surface of recycled coarse aggregate present in the mix. It was also seen that the untreated RAC, N50R50P0% exhibited the least compressive strength at both 7 and 28days.The low in strength can be associated with the high-water absorption rate, high porosity and lower density exhibited by the recycled coarse aggregate.

This result obtained here is comparable with previous studies (Li, L et al. 2021) where nano silica was used as a treatment material.

5.4 Splitting tensile strength of NAC, RAC and treated RAC

As seen in Table 7, at 7 days, the tensile strength of treated RAC was improved more than the untreated RAC, N50R50P0% but at 28 days, there was an increase in the tensile strength of the untreated RAC more than the treated RAC. This sudden increase was unexpected can could be attributed to accelerated curing of the mix which turns out to increase in strength at 28 days. The control mix, N100R0P0%still produces the highest tensile strength at both 7 and 28 days and the treated mix N50R50P0.2% still presented the optimum dosage at 7 and 28days.Generally the splitting tensile strength result is not well pronounced at 28 days and this result is supported by the findings of (Xiao 2018).

5.5 Drying shrinkage and water absorption of hardened concrete

The drying shrinkage can cause cracking of the concrete and thereby exposing the reinforcing bars to corrosion. Through previous studies, RAC are seen to have a low durability performance than the conventional concrete and these low performances can be associated with the weak mechanical properties of RCA. The drying shrinkage of untreated mix N50R50P0% was up to 900 micro strain which is the largest shrinkage among the mix. The addition of graphene helped in lowering of the shrinkage among the treated RAC. At 28 days, the mix N50R50P0.3% exhibited the least shrinkage of about 160 micro strain which is which 66% lower than the shrinkage of the control mix, N100R0P0% and 82% lower than the untreated RAC. The high shrinkage of untreated mix, N50R50P0% was likely to be as a result of the weak mechanical properties of the recycled coarse aggregate. According to AS 1379, the maximum allowable drying shrinkage value is 850 micro strain (Sirivivatnanon & Baweja 2002).The shrinkage was able to be slowed down by the addition of pristine graphene to the RAC mix and this result supports the findings of (Zhu et al. 2021)

5.6 Water absorption of hardened concrete

From figure 20, the water absorption of one of the treated RAC was reduced compared to the untreated RAC and the control mix. This is evidence that the graphene solution was able to reinforce the adhered mortar and fill up completely the void pore spaces present in the recycled coarse aggregate in the mix. The rise in water absorption of the untreated mix can be attributed to the presence of old attached mortar, high porosity as a result of pore spaces etc. Generally, there is a 34% decrease in the water absorption of treated RAC as compared with the untreated RAC.

Generally, at 28 days, the optimum treated RAC produced a compressive strength of 60.74MPa which is 19% more than the untreated RAC and 2.5% less than the conventional mix strength. In terms of durability study, the drying shrinkage and water absorption of treated RAC performed better than the untreated and conventional mix. By these comparisons, I can finally say that I developed a waste-based concrete mix that exhibited similar properties as the conventional concrete mix.

Lastly, the limitation encountered during this research work were the porosity test and microstructural properties analysis. The porosity test was unable to be performed on the treated RCA due to unavailability of the equipment. The scanning electron microscopy (SEM) analysis was unable to be performed on the untreated and treated RCA to enable visibility and proper study of the attached mortar and the interface transition zone due to time constraint. In future studies, the two experiments will be carried out.

Chapter 6: CONCLUSION

In this research, the mechanical properties of untreated recycled aggregate concrete (RAC), treated recycled aggregate concrete, natural aggregate concrete (NAC) with pristine graphene were studied by the compressive strength, splitting tensile strength, drying shrinkage and water absorption.

The water absorption and specific gravity were influenced by the graphene treatment. The water absorption of the treated recycled aggregate was seen to be lower, and the specific gravity was also increased as a result of the pore spaces being filled up by the pristine graphene solution.

The slump values of the mix were seen to be affected by the addition of graphene dosages. It was concluded that the increment in pristine graphene dosage led to the decrease in the slump values of treated RAC.

The results shows that an increase in compressive strength and splitting tensile strength of treated RAC with mix N50R50P0.2% having the optimum dosage of pristine graphene. The improvement can be associated with the pristine graphene repairing the attached old mortar on the recycled coarse aggregate and filling up its pore spaces to increase density and reduction in porosity.

The drying shrinkage of RAC was reduced as a result of graphene addition. This means that the usage of graphene in recycled concrete will protect the concrete by limiting its shrinkage which may lead to cracks and exposure of the reinforcing bars.

Though this treatment involves different stages or process, but it is considered as cost effective because it does not require complicated equipment and graphene which was used as treatment is readily available at cheaper price.

From the positive outcome of pristine graphene on recycled coarse aggregate, it can be concluded that the use of recycled coarse aggregate should be encouraged for the production concrete, not only to reduce amount of C&D going to the landfills but also to save natural coarse aggregates from depletion.

Chapter 7: FUTURE WORK

- The use of recycled aggregate in other concrete works like high performance concrete and precast concrete should be investigated
- The study of long-term durability behaviour of RAC should also be studied
- Study of the effect of oxygen, functionalities on the surface of graphene oxide and reduced oxide.
- Study of the microstructural analysis of the graphene-reinforced concrete to understand the interaction of the interface transition zone.

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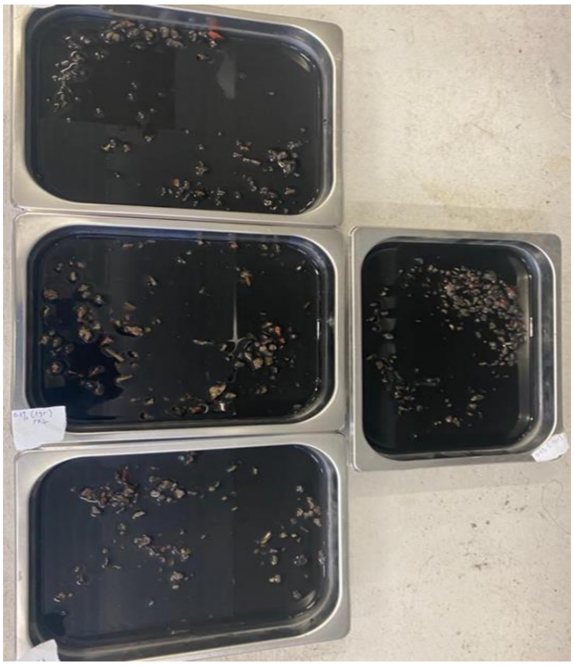
Appendices

(a)

(b)

Figure 21. NCA(a) and untreated RCA(b)



(a)

(b)

Figure 22.Soaked RCA with pristine graphene at different dosages (a) and saturated surface dry treated RCA(b)

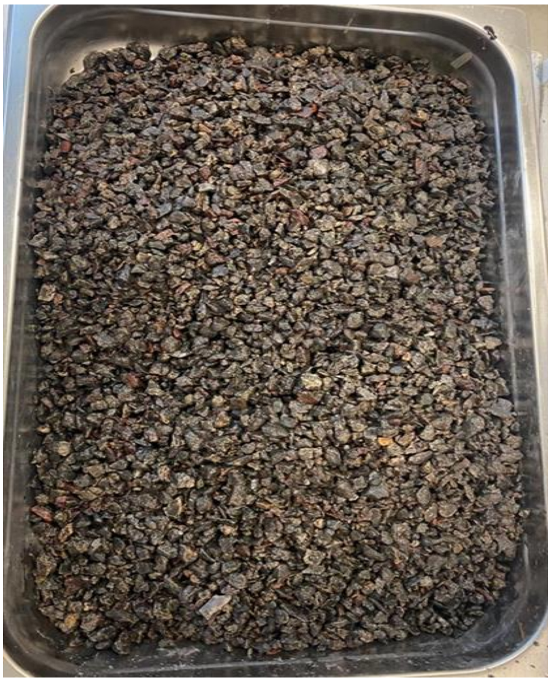


Figure 23. Ready for mix treated RCA

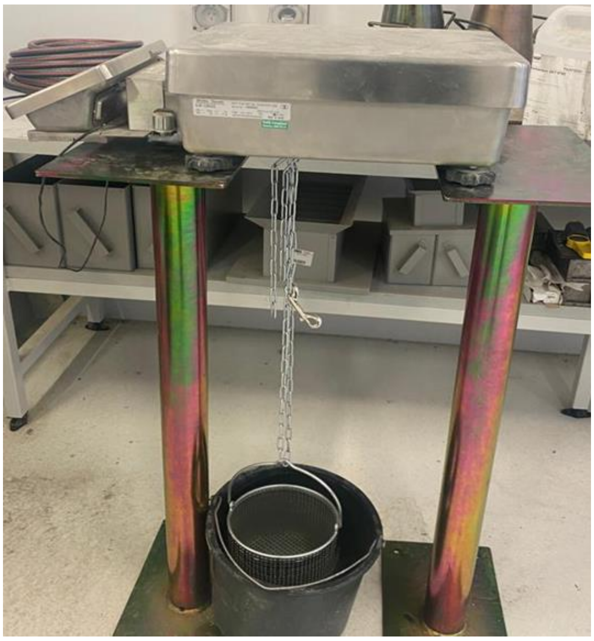


Figure 24.Specific gravity and water absorption test on NCA and RCA

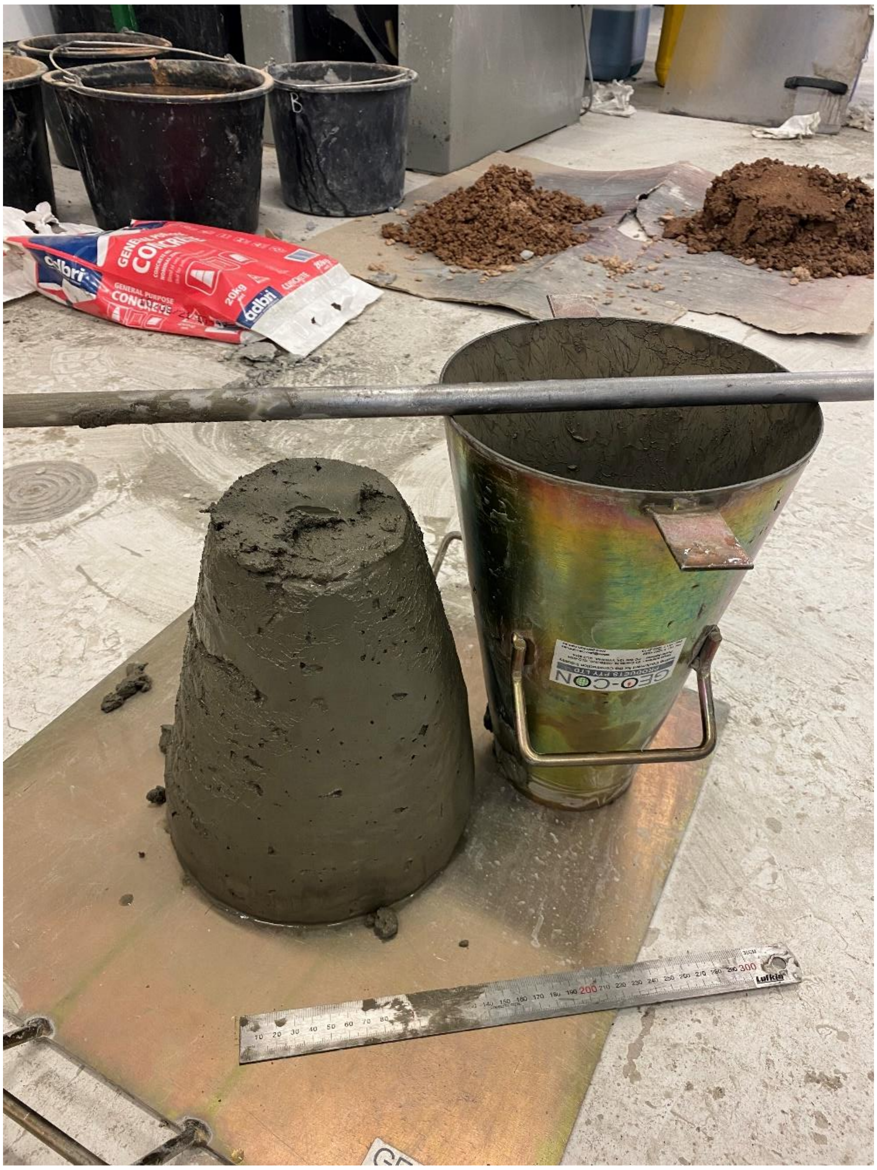


Figure 25.Slump test

Figure 26.Measurement of drying shrinkage on one of the specimens

Figure 27.Specimens for water absorption test

Figure 28. Particle size distribution using the AS method

Table 8.Calculation for the particle size distribution of NCA

	Particle size distribution for Natural Coarse Aggregate (NCA)								
Sieve Size(mm)	Sieve weights(g)	Wt of sieve + NCA retained 1	of sieve + NCA retaine	NCA 1(g)	NCA 2(g)	Avg(g)	% retained	Cumulative % retained	% passing
19	1471.9	1471.9	1482	0	10.1	5.05	0.75	0.75	99.25
16	1430.5	1449.3	1437.4	18.8	6.9	12.85	1.90	2.65	97.35
13.2	1302.2	1446.6	1475.3	144.4	173.1	158.75	23.42	26.07	73.93
9.6	1243.1	1729.5	1703.3	486.4	460.2	473.3	69.83	95.90	4.10
6.7	1207.4	1228.6	1224.4	21.2	17	19.1	2.82	98.71	1.29
4.75	1226.5	1227	1227.6	0.5	1.1	0.8	0.12	98.83	1.17
2.36	1082.2	1082.2	1082.5	0	0.3	0.15	0.02	98.85	1.15
1.18	497.3	497.4	497.6	0.1	0.3	0.2	0.03	98.88	1.12
0.6	450.1	450.3	450.6	0.2	0.5	0.35	0.03	98.91	1.09
0.425	428.1	428.3	428.3	0.2	0.2	0.2	0.03	98.94	1.06
0.3	424.6	424.8	424.9	0.2	0.3	0.25	0.04	98.98	1.02
0.15	393.5	393.5	394.2	0	0.7	0.35	0.05	99.03	0.97
0.075	404.7	407.8	408	3.1	3.3	3.2	0.47	99.50	0.50
Pan	398.1	400.2	400.6	2.1	2.5	2.3	0.34	99.84	0.16

Table 9.Calculation for the particle size distribution for Sand

	Particle size distribution for NS					
Sieve Size(mm)	Sieve weights(g)	Wt of sieve + NS retained 1	of sieve + NS retaine	NS 1(g)	NS 2(g)	Avg(g)
19	1471.9	1471.9	1471.9	0	0	0
16	1430.5	1430.5	1430.5	0	0	0
13.2	1302.2	1302.2	1302.2	0	0	0
9.6	1243.1	1243.1	1243.1	0	0	0
6.7	1207.4	1207.6	1207.4	0.2	0	0.1
4.75	1226.5	1228.4	1227.5	1.9	1	1.45
2.36	1082.2	1087.5	1086.4	5.3	4.2	4.75
1.18	497.3	507.5	506.9	10.2	9.6	9.9
0.6	450.1	528.6	537.8	78.5	87.7	83.1
0.425	428.1	567.7	588	139.6	159.9	149.75
0.3	424.6	596.4	617.5	171.8	192.9	182.35
0.15	393.5	612.6	623	219.1	229.5	224.3
0.075	404.7	451.2	450.6	46.5	45.9	46.2
Pan	398.1	401.9	400.6	3.8	2.5	3.15

Table 10.Calculation for the particle size distribution of RCA

	Particle size distribution for Recycled Coarse Aggregate (RCA)								
Sieve Size(mm)	Sieve weights(g)	Wt of sieve + RCA retained 1	of sieve + RCA retaine	RCA 1(g)	RCA 2(g)	Avg(g)	% retained	cumulative % retained	% passing
19	1471.9	1471.9	1471.9	0	0	0.00	0.00	0.0	100.0
16	1430.5	1430.5	1430.5	0	0	0.00	0.00	0.0	100.0
13.2	1302.2	1302.2	1302.2	0	0	0.00	0.00	0.0	100.0
9.6	1243.1	1263.1	1272.9	20	29.8	24.90	3.67	3.7	96.3
6.7	1207.4	1537.9	1504.2	330.5	296.8	313.65	46.27	49.9	50.1
4.75	1226.5	1449.8	1460.1	223.3	233.6	228.45	33.70	83.7	16.3
2.36	1082.2	1148.2	1172.7	66	90.5	78.25	11.54	95.2	4.8
1.18	497.3	506.3	503.4	9	6.1	7.55	1.11	96.3	3.7
0.6	450.1	453.9	451.8	3.8	1.7	2.75	0.41	96.7	3.3
0.425	428.1	430.3	429	2.2	0.9	1.55	0.23	96.9	3.1
0.3	424.6	427.2	425.9	2.6	1.3	1.95	0.29	97.2	2.8
0.15	393.5	399.5	397.2	6	3.7	4.85	0.72	97.9	2.1
0.075	404.7	409.9	409.1	5.2	4.4	4.80	0.71	98.7	1.3
Pan	398.1	407	407.5	8.9	9.4	9.15	1.35	100.0	0.0

Table 11.Calculation for the properties of treated RCA

Dose of PRG (g)	Dry weight	Pan weight	Pan +soaked RCA	SSD weight	Saturated weight	Pan +Dried RCA	Dried RCA	Specifc Gravity	Water absorption	Bulk Density
0.1	1700	1001.3	2798.9	1797.6	1076.1	2695.8	1694.5	2.348579349	6.1%	2.491476091
0.2	1700.5	949.3	2744.2	1794.9	1074.9	2642.7	1693.4	2.351944444	6.0%	2.492916667
0.3	1700.4	941.7	2729.6	1787.9	1072.7	2633.1	1691.4	2.364932886	5.7%	2.499860179
0.5	1700.1	952.4	2756.2	1803.8	1105.2	2652.3	1699.9	2.433295162	6.1%	2.582021185

Table 12.Properties of aggregates

Volume of Mix	**0.013894131**
SG OF PRGRCA	2.364932886
SG of NCA	2.973201231
SG of RCA	2.310536872
SG of Sand	2.552933035
Density of water (kg/m3)	997
Density of cement(kg/m3)	1440
Mass of NCA	41.18611653
Mass of RCA	32.00659272
Mass of FA	35.36437305
Mass of Cement	20.00754829
Mass of PRGRCA	32.76011069

Figure 29. Image of untreated RCA