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Sustainable concrete with solely recycled and by-product constituents

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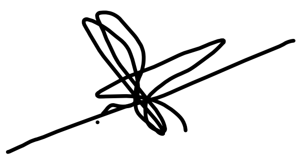

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Abstract

Humans since ancient times have explored their surrounding materials throughout experiments and accumulated experience in the practice of construction, thereby recognising the characteristics of building materials which can most effectively meet their needs. In this context, concrete is one of the most important materials in human civilization, where it is used widely in construction, despite the fact that cement and aggregate production and transport cause the emission of large amounts of carbon dioxide, which is the main cause of global warming. The production of one tonne of cement, for example, causes the emission of about 800 kg of this CO_2. The growing demand for concrete constitutes a threat to the environment and its resources into the future. According to a market study by The Freedonia Group, in 2019 the world demand for cement was 5.1 billion tonnes which means that more than 2.5 billion tonnes of water and more than 11 billion tonnes of aggregates, both of which are scarce resources, will also be consumed. In addition, it is estimated that each year 1 billion tyres end their service life, and the steel industry is producing significant quantities of Ground granulated blast furnace slag (GGBS) as a recyclable material. The 2020 National Waste Report Ireland estimated the total quantity of construction and demolition waste collected in 2017 was 4.7 million tonnes which was collected by authorised waste collectors for treatment. 81% of this consisted of soil and stones, 8% of mixed construction and demolition waste, 7% is concrete, bricks, tiles and 4% are metals. On the other hand, Ireland also experiences from 750 to 1400mm of rainfall in a year. This thesis will use recycled car tyres in the form of chipped rubber, recycled concrete aggregates (RCA) coarse and fine, GGBS, Silica fume, 6.3 mm waste aggregate, recycled Lithium from batteries, and rainwater to design a sustainable concrete. Combining these facts, the objective of this thesis is to describe the 100% substitution of these substances only to form sustainable concrete without compromising concrete mechanical properties. This will demand the pre-treatment of these components to compensate for the natural strength loss due to their inclusion. Therefore, an innovative novel treatment method is selected for recycled concrete aggregates and chipped rubber to be separately treated and tested to mitigate the loss of strength in proposing a novel recycled activator for GGBS and silica fume. Then these waste recyclable materials are combined in a concrete mix that is 100% recycled and, therefore, significantly more sustainable.

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Glossary

Term	Definition
Recycled material	Converted waste materials into new materials
Waste material	Unwanted and unused materials from any industry
By-product material	A secondary material (product) derived from a production process
RCA	Recycled concrete aggregate
CR	Chipped rubber
SF	Silica fume
HRW	Harvested rainwater
GGBS	Ground Granulated Blast Furnace Slag
LiCl	Lithium Chloride
LiOH	Lithium Hydroxide
RS	Recycled sand
SA	Sulphuric acid (H_2SO_4)
Concrete mechanical properties	Strength, workability, density, and elastic modulus.
rubberized concrete	Concrete that contains rubber as an aggregate
W/C	Water to cement ratio
ITZ	interfacial transition zones
RF	Reference concrete mix
RA50MPa	Recycled concrete aggregates 50 MPa of strength
RA35MPa	Recycled concrete aggregates 35 MPa of strength
R Sand	Recycled Sand
RW	Harvested rainwater mix

Chapter 1

Introduction

1. Introduction

Concrete is a key element in the construction and building industry and the second most consumed material after water on earth (Chakraborty and Goswami, 2015). Recently, the world has been moving to a more significant sustainability agenda, which focuses on the relationship between buildings and the environment, in a framework of so-called green buildings or environmentally friendly cities without polluting elements. This is to reduce the negative impact of buildings on the environment, as well as the reduction of construction and operating costs. Therefore, this research will demonstrate the process of designing a wholly sustainable concrete, the main material from which buildings are constructed.

1.1. Background of the study

Since ancient times humans have explored their surroundings through experiments and accumulated experience in the practice of construction, thereby recognising the characteristics of building materials which can most effectively meet their needs. In this context, concrete is one of the most important materials in human civilization, where it is used widely in construction, despite the fact that cement and aggregate production and transport cause the emission of large amounts of carbon dioxide (Sadineni et al., 2011). Buildings account for a substantial share of the energy consumed in developed countries; they are accountable for approximately one third of the total energy emissions and large quantities of carbon dioxide (CO_2) release. Such emissions consist of embodied CO_2 as well as the CO_2 generated from the different phases of the building's life cycle, starting from the production of the material to construction, its operational life and ending with the disposal of the building and its materials (Rakhshan et al., 2013, Monteiro et al., 2017).

Furthermore, the growing demand for concrete constituents in line with population and economic growth is a threat to the environment and the sustainability of global resources into the future. According to a market study by The Freedonia-Group (2020), in 2019 the world demand for cement was about 5.1 billion tonnes which implies that more than 2.5 billion tonnes of water and more than 11 billion tonnes of aggregates, both of which are also scarce resources, have been consumed. In addition, the National Waste Statistics (2020) Report Ireland estimated that the total quantity of construction and demolition waste collected in 2017 was 4.7 million tonnes as collected by authorised waste collectors for treatment. 81% of this consisted of soil and stones, 8% of mixed construction and demolition waste, 7% was concrete, bricks, tiles and 4% are metals. However, it is known that the utilisation of recycled materials in concrete can compromise concrete strength and durability (Tavakoli and Soroushian, 1996, Xiao et al., 2005, Albano et al., 2005, Khatib, 2005, Etxeberria et al., 2007).

This research will suggest and investigate a set of novel and innovative pre-treatment methods for recycled products and by-products to use them in a concrete mix. This is to compensate for the natural strength losses due to their inclusion. The suggested pre-treatments include:

- Surface treating chipped rubber (CR) as an aggregate replacement, made from waste tyres, with ultraviolet light and Sulphuric acid (H_2SO_4).
- Segregating, washing and then drying high strength recycled concrete aggregate (RCA) as a coarse and fine aggregate replacement before surface treating them with micro silica fume (SF).
- Adding Lithium Chloride (LiCl) and Lithium Hydroxide (LiOH) as chemical activators to Ground Granulated Blast Furnace Slag (GGBS) to enhance early age strength development.
- Using 6.3 mm waste limestone aggregate as a coarse aggregate to particle pack the concrete mix.
- Using filtered harvested rainwater (HRW) in concrete as a replacement for normal tap water.

Understandably, the green building materials market is rapidly expanding, and the utilisation of the recycled materials has the potential to create a novel concrete made solely of the recycled constituents.

1.2. Aim of the study

This study aims to use solely recycled materials as constituents to form a novel concrete without adversely affecting its key mechanical properties specifically workability, density, strength and elastic modulus. This will require pre-treatment of some constituents before using them to compensate for the natural strength loss arising from their addition. This study involves mitigating the negative impact of using these recycled materials individually and collectively: ground granulated blast-furnace slag (GGBS) from the steel manufacturing industry, recycled concrete aggregate (RCA) from demolished buildings, recycled tyres in the form of chipped rubber, silica fume (SF) recycled from the silicon industry, Lithium Chloride, Lithium Hydroxide recycled from old batteries and the 6.3 mm waste aggregates from quarries. This will also reduce dependence on less sustainable materials, such as quarried aggregates and Portland cement (PC) and normal tap water. The sustainable novel concrete should match the normal concrete's mechanical properties for it to be considered. specified and used as a structural material.

1.3. Scope

The study scope is divided into three main sections, as follows:

- The first focuses on satisfactorily producing a 100% novel recycled concrete mix.
- The second focuses on enhancing the following mechanical properties of the new 100% recycled concrete mix: workability, density, strength and elastic modulus by pre-treating each of the recycled materials separately before adding it to the concrete mix.

- The final part focuses on recommending a method to combine all the different recycled materials together in one concrete mix relying partly on particle packing theory (PPT) to compensate for the strength loss.

1.4. Thesis structure

Gathering information for this study is based on experimentation and documentation, thus drawing conclusions which will help to achieve the goals of the research. Therefore, this research study relies primarily on an empirical method:

- The first section in Chapter 2 is to review scientific engineering papers and studies that addressed the problems associated with replacing concrete components with recycled constituents:
    - Chipped rubber (CR)
    - Recycled concrete aggregates (RCA)
    - Ground granulated blast-furnace slag (GGBS)
    - Harvested rainwater (HRW)

  And to review the methods that the studies recommended to compensate for the concrete strength and aggregate stiffness losses. And to recommend new treatment methods to innovate some of the existing procedures in pre-treating these recycled materials.
- The second part will be the experimental work described in Chapter 3. The results are illustrated and discussed in Chapters 4 to 7, consisting of the following:
    - Examine the usage of old car tyres in the form of chipped rubber to replace aggregates; To propose a pre-treatment method for chipped rubber in terms of surface enhancement and stiffness development. The aim of this examination is to change chipped rubber surface characteristics and stiffness by pre-treating it with Sulphuric acid (H_2SO_4) and by exposing it to ultraviolet light.

    - Examine the effect of a 100% replacement of normal aggregates with recycled concrete aggregate in the concrete mix on the compressive strength and modulus of elasticity; this test would clarify how the strength of the recycled aggregate can influence the strength grade of concrete. Also, the segregation of waste concrete aggregates based on the original strength before crushing it is expected to contribute positively to achieving the desired properties. Research will also propose the pre-treatment of the RCA by coating with silica fume (SF), which is a by-product of producing silicon metal or ferrosilicon alloys, to enhance the strength and reduce the surface porosity of the RCA.
    - Examine the usage of 6 mm by-product aggregates in a concrete mix and suggest a particle packing method to achieve a greater strength and elastic modulus by adding it to concrete.
    - Examine the replacement of 100% of Portland cement with GGBS and silica fume; proposing the use of waste Lithium Chloride (LiCl) and Lithium Hydroxide (LiOH) as chemical activators to accelerate the strength development.
- The third part, in Chapter 8 will combine the knowledge obtained from the second part with particle packing theory (PPT) to achieve a 100% recycled concrete mix design that has the same mechanical properties specifically workability, density, strength and elastic modulus. of normal concrete.

Figure 1 is relationship model describes the interrelated relations between all different types of materials used in the experimental program undertaken for this thesis. There are four sources of materials that are used in this thesis such as: Recycled materials, waste materials, by-products, and harvested water. For example, construction and demolition wastes are not considered waste after segregating components, they are counted as recycled materials. In Figure 1.1 the blue labelled materials are waste materials, the green are by-products, the red are recycled, the purple are pre-treatments, and the orange are harvested. Furthermore, the bold black arrows are to indicate materials that are combined in the final mix, red arrows to indicate a process and green arrows to indicate a treatment. The goal here is to use these materials to form sustainable novel concrete that is mechanically sound and could be used as a structural material.

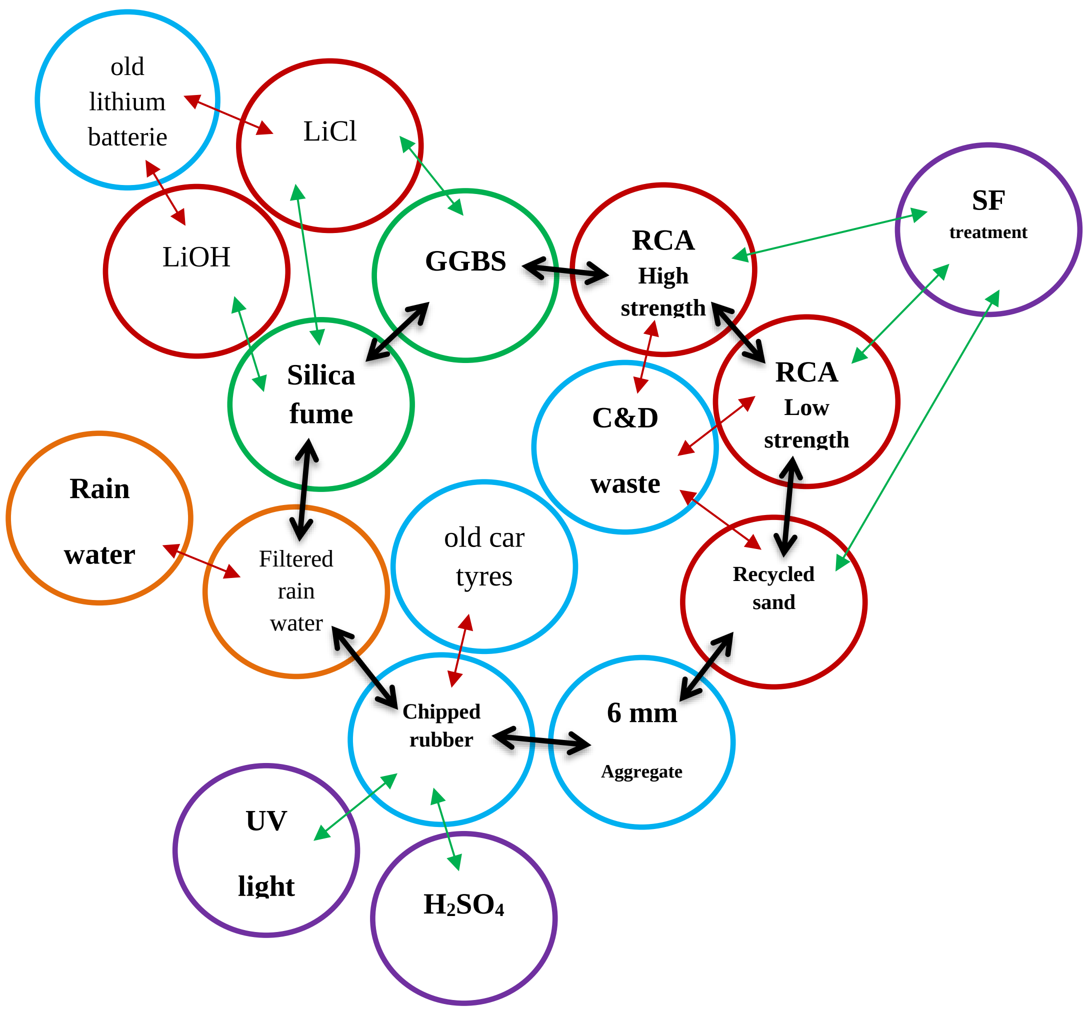


Figure 1.1 Sustainable concrete mix constituent relations diagram

Chapter 2

Literature review

2. Literature review

This chapter is a combination of an exploratory and critical review. It aims to clarify the challenges and the mechanical problems when using recycled and by-product materials to substitute for normal concrete constituents. It also aims to illustrate how scholars mitigate the loss of strength, workability, and density of concrete made with recycled and by-product materials. This chapter will identify the need for additional research to innovate the existing processes of recycled materials pre-treatment and to suggest recycled materials and methods to pre-treat and use in designing a wholly sustainable concrete mix that is only made from recycled and by-product materials.

The literature will cover: chipped rubber, recycled concrete aggregates, silica fume, lithium, GGBS, rainwater harvesting and particle packing, all in relation to their usage and effect on the concrete's mechanical properties.

2.1. Rubber in concrete

About 1.4 billion tyres are sold each year and they fall into the waste category after the end of the tyre's life (Thomas and Gupta, 2015). Regardless of the service life span of the tyres, it is estimated that every year almost one billion tyres end their service life of which more than 50% are dumped in landfills without any treatment (Thomas et al., 2015). Numbers are increasing because of the growing vehicle numbers and traffic worldwide (Thomas and Gupta, 2015, Jokar et al., 2019). Studies have been conducted to develop techniques that combine concrete technology with chipped rubber (Albano et al., 2005). Waste tyre rubber is added to concrete as a substitute for coarse and fine aggregate or sand. The studies revealed that the addition of chipped rubber to concrete could improve the elastic behaviour and sound insulation but reduced the compressive strength (Al-Tayeb et al., 2013, Yung et al., 2013, Jokar et al., 2019). Nevertheless, suggestions were made on how to control the loss of strength; it might be minimized by a prior surface treatment with sodium hydroxide ($NaOH_2$) applied to the rubber particles to be used in the concrete (Yung et al., 2013).

Waste tyres are classified based on size to be used in concrete into shredded, chipped, crumb and ground rubber as explained below (Heitzman, 1992, Segre et al., 2003, Reda Taha et al., 2008, Ganjian et al., 2009, Li et al., 2020)

- Shredded rubber in the range 100 – 400 mm
- Chipped rubber to replace coarse aggregate in the range 13 – 75 mm
- Crumb rubber that replaces sand in the range 0.425 - 4.75 mm
- Ground rubber that may be used as a fine filler in the range 0.075–0.475 mm

Moreover, Reda Taha et al. (2008) used chipped and crumbed tyres rubber particles to replace coarse and fine aggregates, respectively. The chipped rubber was segregated into two sizes from 5 to 10 mm and from 10 to 20 mm. The two sizes of the chipped rubber particles were mixed in a ratio of 1:1. And the crumb rubber particles are ranged from 1 to 5 mm. Figures 2.1 a and b show the sieve analysis of the fine and coarse aggregate along with the chipped and crumbed tyre rubber particles. Figure 2.2 by Khaloo et al. (2008) shows crumb and chipped rubber actual size.

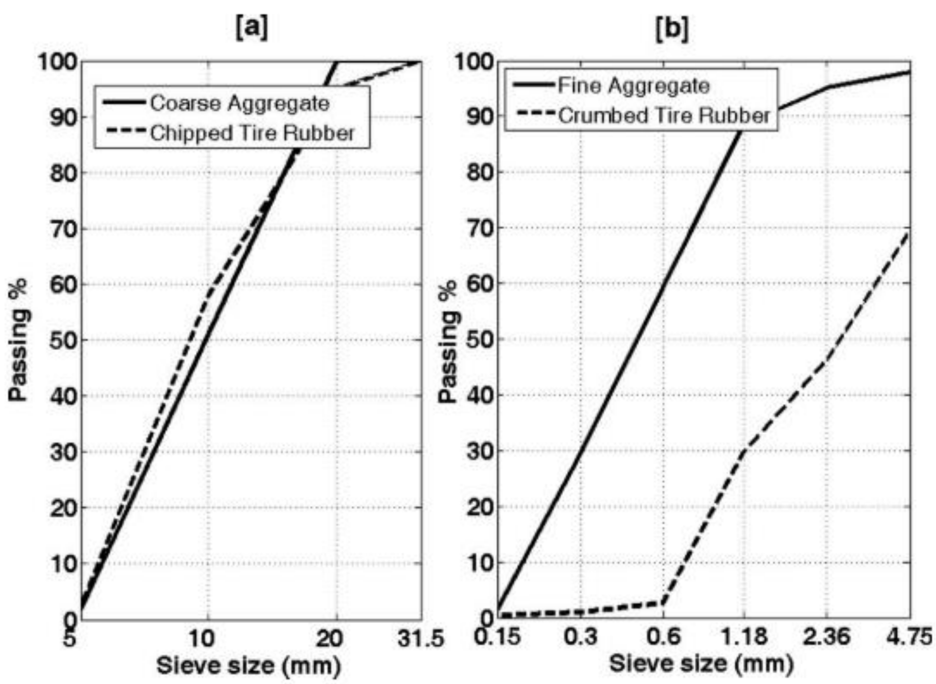


Figure 2.1 Sieve analysis of tyre rubber particles with respect to coarse and fine aggregate (Khaloo et al., 2008)

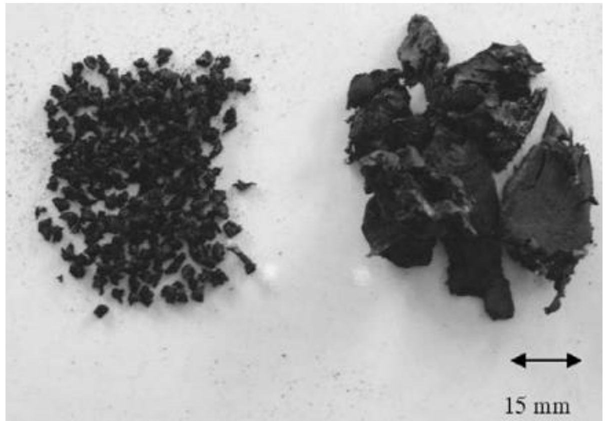


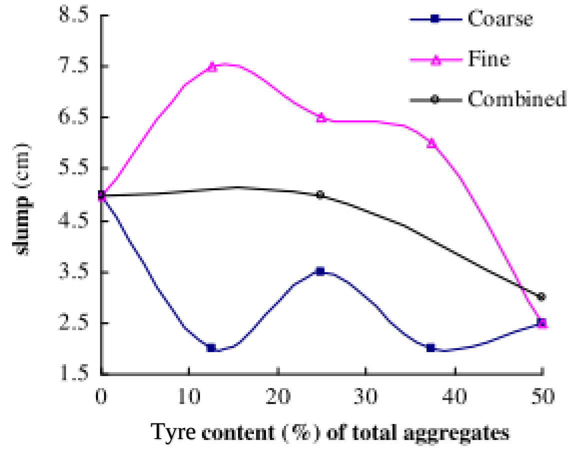
Figure 2.2 (a) crumb rubber, (b) chipped rubber particles (Khaloo et al., 2008)

2.1.1. Workability of chipped rubber concrete

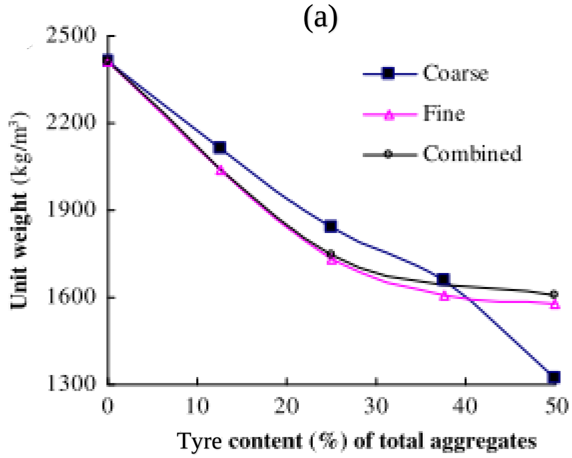
The workability of fresh rubberised concrete, defined by Khaloo et al. (2008) as the state in which concrete can be mixed, transported and placed easily, is affected by the interactions of the tyre particles and mineral aggregates. The study categorized chipped rubber replacement into three labelled categories: C: coarse aggregates, F: fine aggregates and CF: course and fine aggregates. They concluded that the slump for the C mixes decreased from 50mm to a minimum value of 20 mm with rubberized aggregate concentrations of 15%. On the other hand, the slump for otherwise similar F mixes increased with rubberized aggregate concentrations of 15% and reached a value of 75 mm. Table 2.1 shows the concrete mix design and Figure 2.3 illustrates slump values and unit weight.

Table 2.1 Concrete mixture proportions (Khaloo et al., 2008)

Specimen	Water (lit)	Cement (kg)	Coarse tyre aggregate (kg)	Fine tyre aggregate (kg)	Gravel (kg)	Sand (kg)
P	227	350	0	0	900	900
C25	229	350	152.375	0	675	900
C50	299	350	304.18	0	450	900
C75	356	350	456.3	0	225	900
C100	442	350	609.5	0	0	900
F25	215	350	0	149.5	900	675
F50	282	350	0	299	900	450
F75	384	350	0	452.1	900	225
F100	453	350	0	602.8	900	0
C25F25	298	350	152.375	149.5	675	675
C50F50	434	350	304.2	301.4	450	450



(a)



(b)

Figure 2.3 Properties of fresh concrete (a) slump and (b) unit weight of fresh rubberized concrete mixtures (Khaloo et al., 2008)

The authors did conclude that a pre-treatment of chipped rubber particle surfaces should be considered for possible improvement on the concrete’s mechanical properties. Despite that in Figure 2.3a the authors did not discuss the slump behaviour with the 25% rubber content. This could be due to particle packing's effect on workability which was not mentioned. Thus, in this thesis the effect of particle packing will be examined and used to enhance rubberized concrete workability and perhaps strength.

A similar study by Zheng et al. (2008) but with a smaller rubber aggregate size, also experienced a slump decrease with an increase in rubber content. Their average slump was reported to have decreased from 140 mm to 80 mm with increasing percentages of chipped rubber such as that shown in Figure 2.4a. Concrete mixes made with fine ground rubber decreased the slumps between 110 mm to 60 mm depending on the percentage of fine ground rubber as shown in Figure 2.4b. The mix design for this rubberized concrete mix is shown in Table 2.2

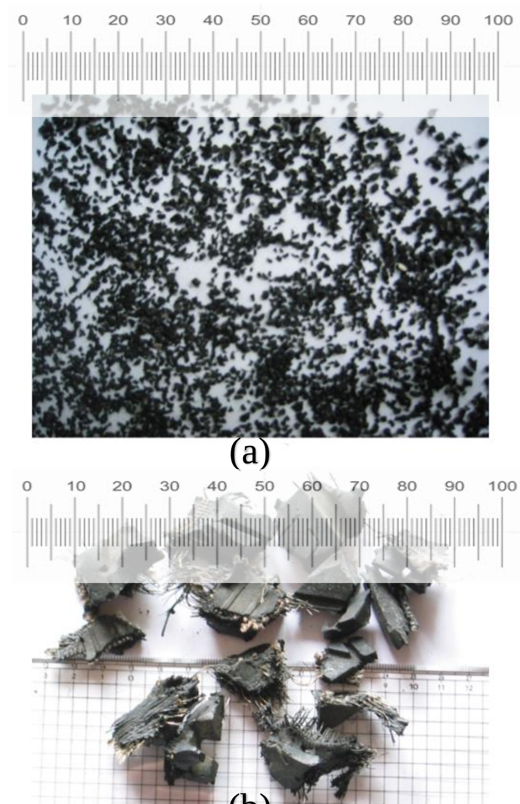


Figure 2.4 (a) Fine ground rubber, (b) Crushed rubber chips (Zheng et al. 2008).

Table 2.2 Mixture proportions for control concrete and rubberized concrete (Zheng et al. 2008).

Materials (kg/m^3)	Normal concrete	Rubberized concrete sets GR-8			Rubberized concrete sets CR-40		
		Set-15	Set-30	Set-45	Set-15	Set-30	Set-45
Water	180	180	180	180	180	180	180
Cement	401	401	401	401	401	401	401
Sand	660	660	660	660	660	660	660
Coarse aggregate	1180	1003	826	649	1003	826	649
Water reducer	4.01	4.01	4.01	4.01	4.01	4.01	4.01
Ground rubber (GR-8)	0.00	36.7	73.4	110.2	–	–	–
Crushed rubber (CR-40)	0.00	–	–	–	75.8	151.5	227.3

Thomas and Gupta (2015) observed that the density of concrete, as shown in Table 2.3, decreased with increasing percentages of rubber. This is due to the lower specific gravity of rubber which has a relative density value of about 0.9 compared to about 2.7 for normal aggregates.

Table 2.3 Density of rubberized concrete (Thomas and Gupta, 2015)

Mix ID	C	CS	W	F.A	C.A	RT	Density T/m^3	Compaction factor
RT 5	350	0	140	896	1083	57	2.334	0.93
RT 10	350	0	140	896	1026	114	2.310	0.93
RT 15	350	0	140	896	969	171	2.204	0.92
RT 20	350	0	140	896	912	228	2.104	0.91
CS40, RT10	350	358.4	140	537.6	1026	114	2.220	0.91

C: Cement, CS: Copper Slag, W: Water, FA: Fine Aggregate, CA: Coarse Aggregate, RT: Discarded rubber tyres. RT5: Rubber Tyres 5% Replaced, etc.

Su et al. (2015) observed the relationship between chipped rubber particle size and slump decrease, which they attributed to the results of a density test for fresh concrete where a clear reduction in the concrete fresh density and hence slump was observed irrespective of the rubber particle size.

Yet again, this study did not mention whether this was related to the change in particle packing or not and did not investigate any pre-treatment methods on the rubber, which will be investigated in this thesis.

All previous research in this area did not mention the effect of rubber surface grip on the decrease of slump, as car tyres in the first place are designed to provide grip to surfaces. This thesis will investigate this and propose a pre-treatment method to smoothen the chipped rubber particles surface. Doing that will help to get the real slump reading without the interference of rubber surface grip on the result. On the other hand, failing that means that the slump test is not suitable for testing the workability of rubberized concrete and other tests should be investigated such as rheology.

2.1.2. **Rubber concrete water absorption**

It was found that using chipped rubber as an aggregate increases the water demand because rubberized concrete needs higher water content to maintain a similar workability in all concrete mixes. It may also be because of the greater void volume between chipped rubber and cement paste, an increase of around 15% in the water to cement (w/c) ratio with a replacement of 15% of aggregates by chipped rubber (Bravo and de Brito, 2012). Similarly, Kumar Mehta and Monteiro (2014) found that concrete made with rougher aggregate shows greater water demand due to more of the water being used to coat a large surface area of aggregate. However, chipped rubber as an aggregate has a very low water absorption rate Table 2.4 shows the water absorption is about 1% for the 20mm and between 5% to 8.9% for the 10mm this is due to the contamination level of the 10 mm of the tested sample (Raffoul et al., 2016, Raffoul et al., 2017, Siddika et al., 2019).

Table 2.4 Rubber aggregates water absorption

Material (size in mm)	Apparent density (t/m^3)	Oven dry density (t/m^3)	SSD[a] density (t/m^3)	Water absorption (%)	Specific gravity	Bulk density (t/m^3)
Rubber (0–5)	0.80[b]	–	–	–	–	0.40–0.46
Rubber (5–10)	1.10–1.20	1.00–1.10	1.10–1.2	5.30–8.90	1.10	0.45
Rubber (10–20)	1.10	1.10	1.10	0.80–1.30	1.10	0.48

This could only mean that workability in rubberized concrete is not directly related to the water content as chipped rubber has a low absorption rate. This thesis will be re-examining the chipped rubber water absorption rate.

Perhaps Raffoul et al. (2016) should have mentioned whether the chipped rubber was obtained from more than one source or not. This will also be explored in this thesis. Bravo and de Brito (2012) compared the water absorption of: Rubberized concrete made with fine, mechanically-ground rubber, and rubberized concrete made with fine cryogenic rubber (Figure 2.5). They concluded that “because of the rougher aggregate’s greater capacity to bond to the cement paste, thereby water is compensating for the extra voids created by the roughness of the aggregate”.

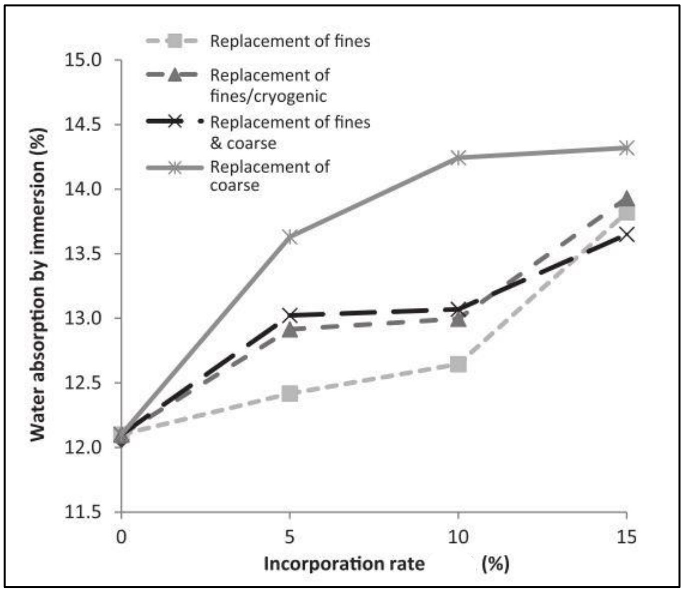


Figure 2.5 Water absorption by immersion of the concrete mixes, incorporation rate of rubber aggregates (Bravo and de Brito 2012)

2.1.3. Compressive strength

Using recycled rubber in concrete usually leads to a lower concrete compressive strength (Son et al., 2011). This reduction in strength is caused by the hydrophobic nature of the rubber material and the stiffness difference between rubber particles and cement paste. The hydrophobic nature leads to imperfect bonding between the chipped rubber aggregate and cement paste where interfacial cracks can easily be generated under external load (Shu and Huang, 2014, Brand and Roesler, 2017, Guo et al., 2017). Furthermore, Reda Taha et al. (2008) in their microstructural investigation on rubberized concrete, concluded that the reduction of strength might be attributed to the behaviour of the tyre rubber particles as a weak flexible aggregate, instead of the reduction of bond between rubber particles and cement paste. The compressive strength reduces consistently as the percentage of rubber increases for a given w/c ratio and curing period (Gesoglu and Guneyisi, 2007). Furthermore, Bravo and de Brito (2012) concluded that the loss of strength of rubberized concrete is greater by a smaller margin when fine aggregate is replaced rather than coarse aggregate. In Figure 2.6 Valadares (2009) shows results for compressive strength test on rubberized concrete mixes.

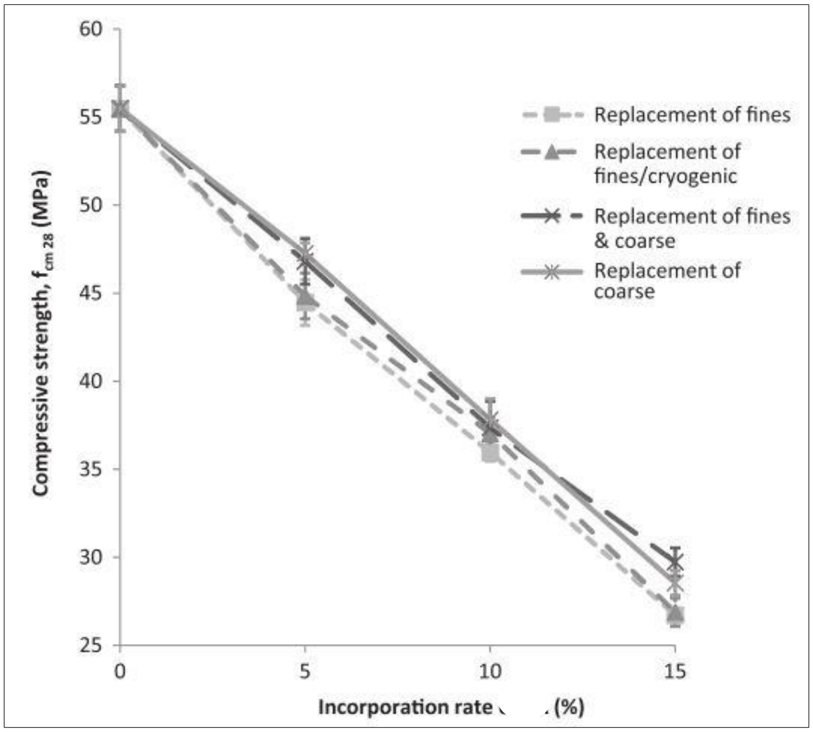


Figure 2.6 28-day compressive strength of the concrete mixes with tyre aggregates, incorporation rate of rubber aggregates (Valadares 2009)

2.1.4. **Failure type**

Under compressive loads, concrete cylinders with high chipped rubber contents were categorized by bulging and diagonal cracking failure which started at the top of the cylinder and spread downwards (Figure 2.7) (Raffoul et al., 2016, Miller and Tehrani, 2017, Raffoul et al., 2017). Also, it was observed that the higher the chipped rubber content the greater the lateral deformations prior to failure. Moreover, rubber particles were able to hold the cylinders intact when they reached the peak load. Toutanji (1996) pointed out that specimens were cracked, but they remained able to withstand some load, due to the fact that rubber aggregates are highly elastic and have the ability to resist large deformations.

Figure 2.7 Large transverse deflection observed in rubberized concrete specimens with 100% rubber content (Miller and Tehrani, 2017)

2.1.5. Tensile strength

Tensile strength of concrete was reduced by the replacement of normal aggregates with rubber. Although rubber is an elastic material and should act as a barrier against crack growth, yet, tensile strength in concrete containing rubber as an aggregate should be opposite of this hypothesis because compressive strength drops. The reason may be due to weak bonding between the two materials and crack expansion reaching rubber particles causes a surface segregation between rubber and the cement paste (Ganjian et al., 2009). Moreover, Aly et al. (2019) concluded that the increase of rubber content in the concrete mix resulted in a regular decrease of splitting tensile strength. For a 10% aggregate replacement, the splitting tensile strength was 2.3 MPa compared to control mix at 3.6 MPa. Furthermore, when chipped rubber replacement was increased by 20% and 30%, it was observed that the splitting tensile strengths decreased by 20% and 35% respectively, compared to the control mix. Table 2.5 shows the mix constituents for the tensile results, C: Refers to control geopolymer concrete mixture with ground granulated blast furnace slag. M: Refers to geopolymer concrete mixture with ground granulated blast furnace slag; The number refers to the percentage of aggregates replacement with crumb rubber.

Table 2.5 Mixtures constituents (kg) per 1 m3 (Aly et al., 2019).

Concrete Mix (ID)	Slag	H2O	NaOH	S.S	Sand	Coarse	Rubber Mesh 40	Rubber 1–4 mm
C	500	36.344	195.204	75.53	525	975	0	0
M1	500	36.344	195.204	75.53	472	877.5	17.83	7.64
M2	500	36.344	195.204	75.53	420	780	35.66	15.283
M3	500	36.344	195.204	75.53	367	682.5	53.49	22.92

2.1.6. Flexural strength

Ganjian et al. (2009) concluded that after breaking the concrete samples in a flexural strength test, it was observed that chipped rubber could be easily removed from the concrete, compared to the other mixes that contained powdered ground rubber. Figure 2.8 shows flexural strength for different levels of rubber replacement. Failure can occur before concrete reaches its ultimate strengths in the compression region due to the low tensile strength of concrete, as well as the lack of good bonding between rubber particles and cement paste (Deshpande et al., 2014). This is confirming similar findings cited in section 2.1.5.

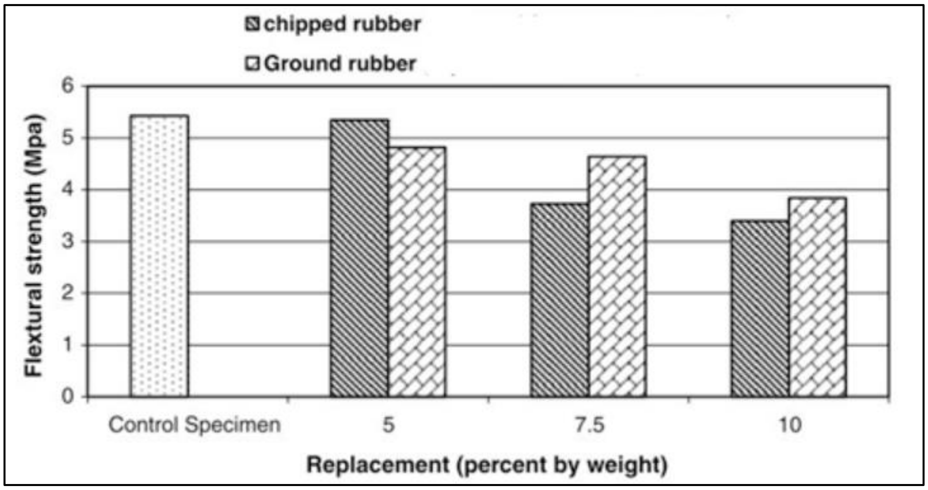


Figure 2.8 Results of flexural strength test (Ganjian et al. 2009)

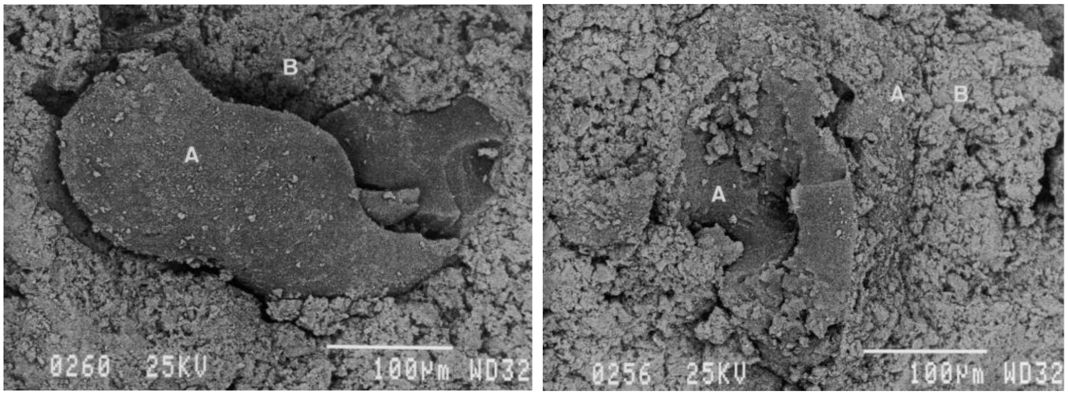
2.1.7. Rubber fibres perform better than chips

Li et al. (2004) concluded that waste tyre fibres perform better when mixed with concrete than waste tyre chips. A possible reason for that may be because of the difference between their load transfer capabilities; "chips do not have enough length to transfer the applied load through an interfacial frictional force, while fibres have longer length to transfer the applied load, resulting in a higher strength", but there is no special machine to cut waste tyre fibres.

2.1.8. Rubber surface treatment with sodium hydroxide

Li et al. (2004) suggested that rubber surface treatment with sodium hydroxide does not work for waste tyre chips, although it works on ground rubber, which was due to its larger surface area that insured more surface contact and more exterior chemical reactions. Furthermore, another report stated that prior treatment of rubber with sodium hydroxide (NaOH) did not produce significant changes to the concrete`s compressive strength or splitting tensile strength, when compared to the untreated rubber (Albano et al., 2005).

Moreover, Segre and Joekes (2000), in their study, surface treated the rubber particles with saturated NaOH for 20 min before using them. They concluded that rubber particles thus treated exhibited better cohesion with the cement; this was tested by Scanning electron microscopy (S.E.M.). Figures 2.9 a and b illustrate the differences between chipped rubber with and without treatment. However, this worked on smaller particles more effectively than larger particles regarding minimizing of the compressive strength reductions.



(a) (b)

Figure 2.9 S.E.M. image of fracture surface of cement test specimen with 10% by mass

a) chipped rubber,

b) NaOH-treated chipper rubber (Segre and Joekes, 2000).

2.1.9. Rubber surface treatment with sulfuric acid

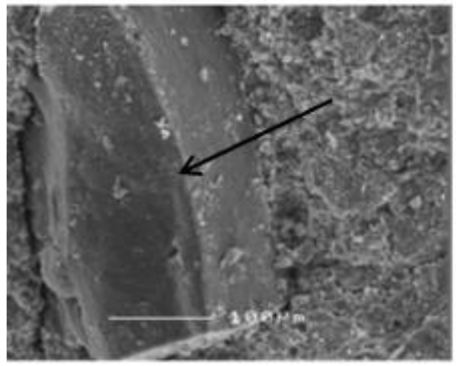
The treatment of rubber with sulfuric acid (H_2SO_4) produces a noticeable decrease in contact angle which was mainly ascribed to an increase in surface energy due to the formation of sulfonic acid moieties and $C=O$ bonds, and the removal of zinc stearate (Cepeda-Jiménez et al., 2000). Moreover, the rubber surface swelled and became brittle and, when flexed, microcracks were created. Also, a rubber surface layer modification was produced with a consequent decrease in tensile strength, though it was not tested in concrete. This treatment enhanced the strength of the rubber's adhesive properties. The optimum immersion time in the H_2SO_4 solution was less than 1 minute and the reaction time in air was not found to be critical; the subsequent neutralization, with ammonium hydroxide, of the high concentration of the H_2SO_4 (95%) was essential in producing adequate effectiveness of the treatment (Cepeda-Jiménez et al., 2000).

Rubber treatment with H_2SO_4 illustrated that this treatment modified the surface chemistry of the rubber, giving rise to a noticeable improvement in wettability and some cracks (depending on the styrene content in the rubber) were created on the surface. The treatment affected not only the surface, but the bulk rubber, producing a noticeable decrease in tensile strength without a significant loss in elongation-at-break. The treatment with sulphuric acid increased the immediate and final adhesion (Cepeda-Jiménez et al., 2001). The treatment of rubber with H_2SO_4 was carried out following different repeated steps: (1) Immersion of the rubber in concentrated acid; (2) Removal of the rubber from the acid and allowing it to continue to react in air for 1 minute; (3) Neutralization using hot distilled water and/or ammonium hydroxide (15% by wt.), followed by exhaustive washing with distilled water (the neutralization was carried out until a pH of 7 was obtained in the washing water); (4) Drying off the treated rubber (Cepeda-Jiménez et al., 2000, Cepeda-Jiménez et al., 2001).

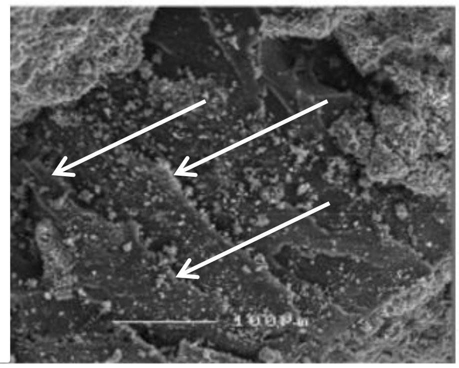
2.1.10. Rubber surface treatment with ultraviolet light

The effect of ultraviolet light (UV) rays on polymers is well recognized (Sivaram, 1997) where UV light can modify the surface of polymers through a range of mechanisms. Some, like photo oxidation, generate free radicals in the presence of air which can cross-link the polymer chains, thereby raising the stiffness and reducing toughness. Furthermore, the presence of free radical species, polar groups and dangling bonds, together acting with the changes in surface free energy, is thought to be the reason why UV exposure is effective in improving adhesive bonding to such surfaces (Sivaram, 1997, Weibel et al., 2009, Ossola and Wojcik, 2014).

SEM fractography in Figure 2.10 exposes changes in the degree of cement debris on the surface of the rubber particles. Furthermore, poor adhesion (hence poor surface coating) might affect the structure of the interface region. The existence of interfacial voids would be expected to reduce as the bonding improved. The microstructural analysis detected visible differences in the fraction of remaining cement debris on exposed rubber particles. This is evidence of a better rubber to cement contact for UV treated specimens. Finally, they concluded that using a UV based pre-treatment on the chipped rubber reduces the strength losses (Weibel et al., 2009, Ossola and Wojcik, 2014).



(a)



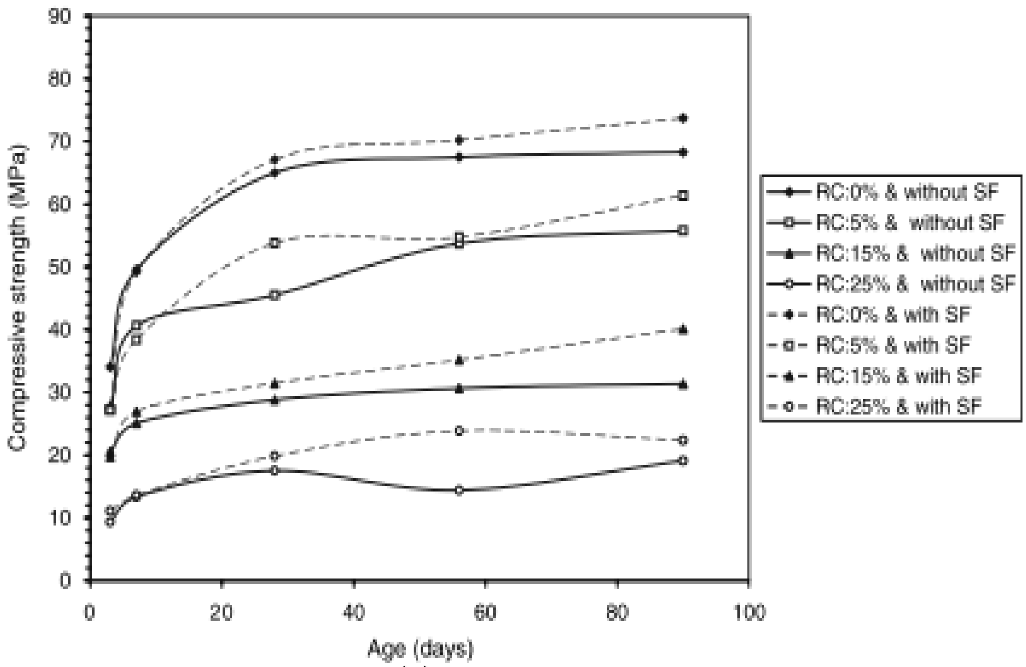
(b)

Figure 2.10 SEM fractography of representative specimens, all showing particulate matter (lighter spots) on embedded rubber particles. (a) (no UV) and (b) (60 hrs of UV) (Ossola and Wojcik, 2014)

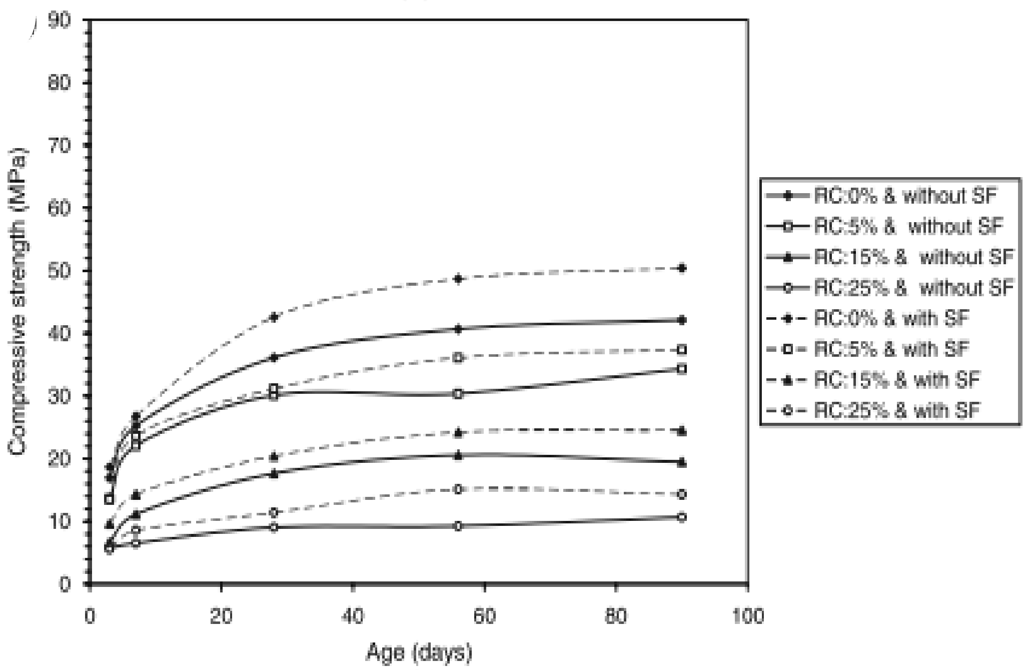
Black arrow is pointing at the chipped rubber and the white arrow pointing at cracks in chipped rubber particle

2.1.11. Using silica fume with rubber

Gesoglu and Guneyisi (2007) stated that there was a systematic reduction in compressive strength with increasing chipped rubber content for the concretes with and without silica fume, but at latter age (90 days), test results illustrated in Figure 2.11 shows that silica fume was very effective in increasing the compressive strength of rubberized concretes. They explained that it was expected because of the good adhesion between the rubber and the cement that includes ultra-fine silica fume.



(a)



(b)

Figure 2.11 Compressive strength development of plain and rubberized concretes with and without silica fume (a) w/c ratio: 0.40 and (b) w/c ratio: 0.60 (Gesoglu and Guneyisi 2007)

2.2. **Recycled aggregates**

The use of recycled and by-product materials requires a strong understanding of their characteristics, which can be problematic because the inconsistency of the material characteristics can be high. Thus, innovative material pre-treatment methods can help to minimize this variability to some extent (Dhir et al., 2019a). Furthermore, it is difficult to overcome the barriers that prevent the wider use of recycled aggregates in construction (Silva et al., 2017), where barriers are demonstrated in Figure 2.12.

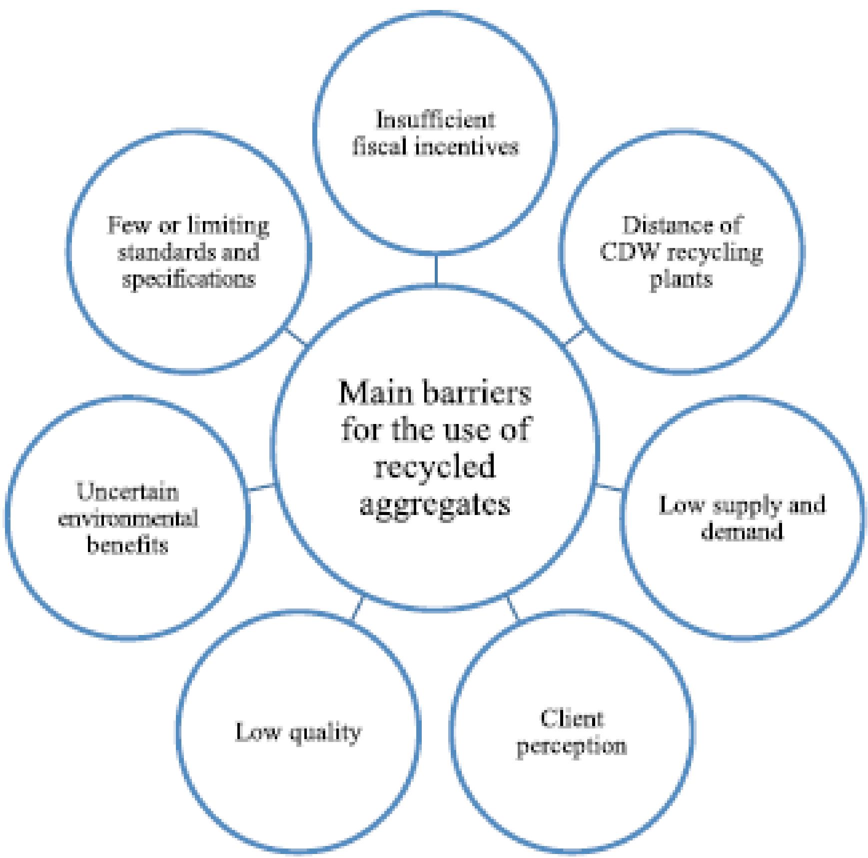


Figure 2.12 Main barriers that prevent a wider use of recycled aggregates in construction (Silva et al., 2017)

Silva et al. (2014) stated that the amount of waste generated by the European union in 2014 was over 2.5 billion tonnes and 33% (870 million tonnes) of that waste was from construction and demolition activities (Figure 2.13). Moreover, eurostat (2019) illustrated that in 2016 the amount of construction waste in the European union increased by 2.5% (Figure 2.14). However, one sustainable solution for this vast amount of waste debris is to recycle it as new concrete aggregate. Through a process of crushing waste concrete to produce recycled concrete aggregates to add in a new concrete mix, one can achieve a more environment-friendly concrete (Rahal, 2007). By using a deconstruction approach of a building, it is likely to retrieve a greater amount of reusable materials (WARP, 2003, Silva et al., 2017).

Waste concrete can be crushed into either fine or coarse aggregates. Recycled concrete aggregate (RCA) are composed of adhered mortar and original aggregates. Thus, in comparison with normal aggregates, recycled concrete aggregates have a higher water absorption ratio and a lower specific gravity. Also, the crushing values and the Los Angeles abrasion percentages are much higher. (Topçu and Şengel, 2004). Therefore, the properties of RCA must be enhanced in order for it to work effectively in load-bearing structures (Wang et al., 2013, Matias et al., 2013, Silva et al., 2014). The mechanical characteristics of RCA largely depend on the type of recycled aggregate used. RCAs are expected to result in an increase in the water absorption of concrete, at a rate directly proportional to the RCA content (Paine and Dhir, 2010, Dhir et al., 2019b).

This thesis will suggest a pre-treatment method to mitigate the water absorption in recycled concrete aggregate, that will ease the use of extra water which will benefit the strength of concrete made from recycled concrete aggregates.

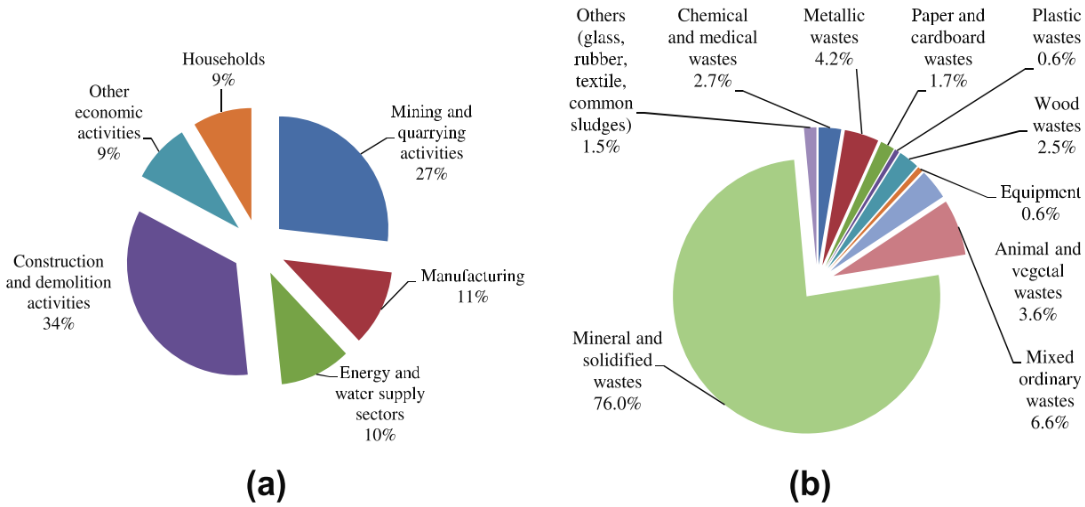


Figure 2.13 Total waste generated in European Union according to: (a) economic activity; (b) waste category (Silva et al., 2014).

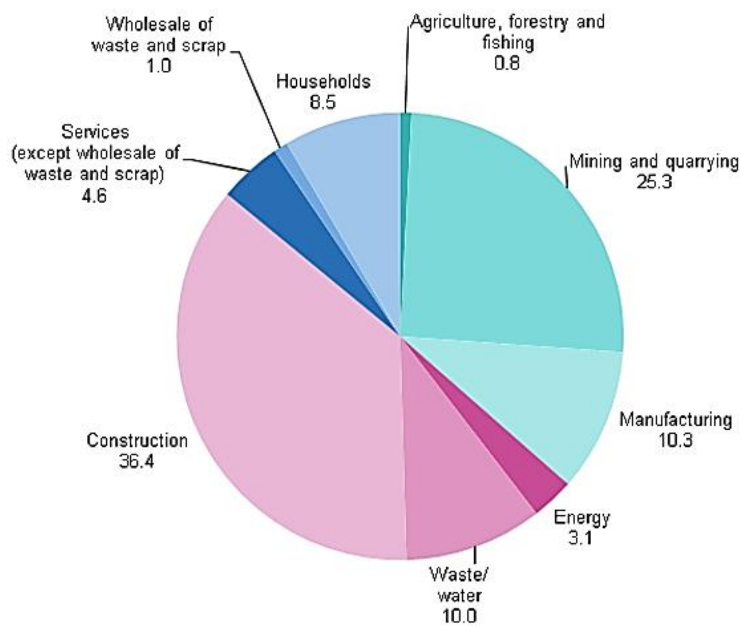


Figure 2.14 Waste generation by economic activities and households in percentage (eurostat, 2019)

2.2.1. Recycled aggregate effect on concrete properties

Replacing normal aggregates (NA) with RCA effects the concrete properties (Silva et al., 2014, Silva et al., 2015a, Silva et al., 2015b, Silva et al., 2017, Dhir et al., 2019b). Yehia et al. (2015) also stated that some of the properties that are affected by the replacement of NA with RCA include: durability, compressive strength, fresh concrete properties, flexural strength, modulus of elasticity, split tensile strength and specific gravity. Moreover, they tested and evaluated the RCA aggregates properties and compared them with NA. The values obtained from the evaluation of the physical and mechanical properties are presented in Table 2.6. The level of water absorption for recycled aggregates is high, and this thesis will propose a method of pre-treatment that will mitigate the water absorption rate.

Table 2.6 Summary of the tests results: Virgin = (normal), and recycled aggregate properties (Yehia et al., 2015)

Property	Virgin aggregate	RA
Absorption	1–2.5 %	1–8.5 %
Specific gravity	2.4–2.7	2–4.8
Crushing value	15–20 %	20–35 %
L.A abrasion	15–30 %	25–65 %
Sodium sulfate soundness (mass loss)	7–21 %	5–36 %

The results showed that RCA has higher absorption capacity due to the mortar adhered on the surface, higher abrasion loss, high crushing value, and soundness loss which could be related to previous exposure to weathering and loading. In addition, RCA consists of three phases: the aggregate phase, mortar phase and the interfacial transition zones (ITZ) between the coarse aggregate and adhered mortar. Figures 2.15 a, b and c are drawings of natural aggregate concrete and RCA. The drawings display the difference in the matrix between two concrete mixes. Therefore, these three phases are largely responsible for the limitations in the properties of RCA.

Consequently, it needs more attention regarding the performance of concrete when RA is to be used in concrete. In practice, RCAs are obtained from different types of construction and demolished structures, and as a result the properties of these RCAs obtained from various sources also vary from structure to structure (Behera et al., 2014).

Therefore, for this study it is suggested that RCAs are categorized based on strength, washed to remove quarry dust and then coated to eliminate differences in the ITZ before being used in concrete.

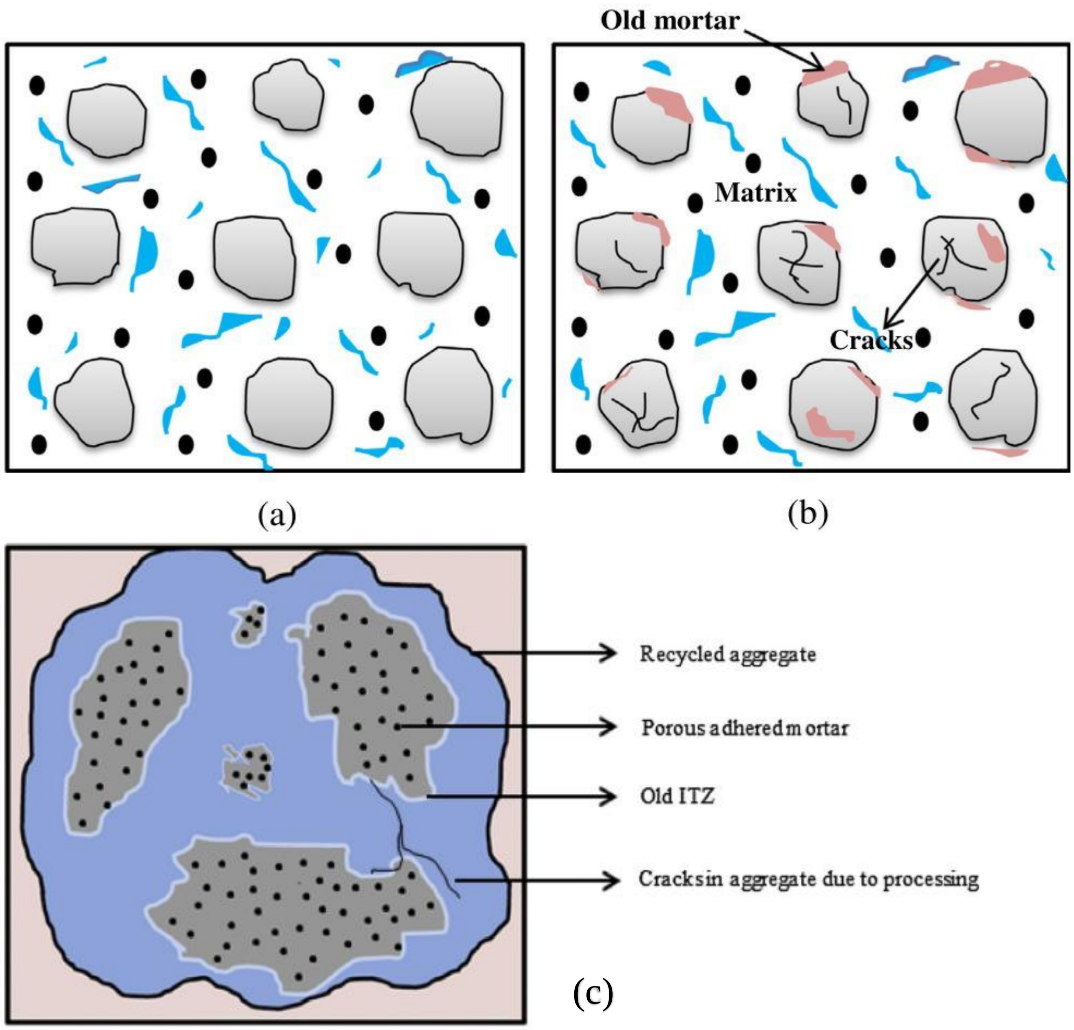


Figure 2.15 Difference between matrixes of (a) natural aggregate concrete and (b) recycle aggregate concrete (c) pictorial representation of physical characteristics of recycled aggregate (Behera et al., 2014).

2.2.1. **Water absorption of recycled concrete aggregate**

RA has a high porosity of mortar, which influences the water absorption rate. Furthermore, a high absorption volume of the RCA means that it needs more water than NA for it to obtain the same workability of a concrete mix. Therefore, to produce an RCA similar to normal concrete it is highly recommended to establish the RCA potential absorption over time, so that it will be reflected in the w/c ratio. However, pre-saturation of the RCA will negatively affect the compressive strength of the concrete. Adding extra mixing water is a better solution to counter the water absorption (Ferreira et al., 2011, Thomas and Gupta, 2013, da Silva et al., 2015, Thomas et al., 2018).

2.2.2. **Workability of recycled concrete aggregates concrete**

When using RCA in concrete, more water is needed to achieve similar workability to that of normal concrete and that is due to the higher absorption capacity of the RCA which is related to the presence of attached porous cement hydrates on the RCA. Moreover, if the RCA content increases in the concrete mix, the workability reduces for the same w/c ratio. However, there is no significant effect concerning the air content up to 25% replacements (Yehia et al., 2015). In addition, in Bravo et al. (2015) they concluded that to keep the slump constant, it was necessary to increase the w/c ratio of some of the mixes as the replacement ratio with RCA increased. However, this mostly happened when fine RCA were used.

Measuring the porosity of recycled aggregate and then coating it with a cementitious material will be investigated in this thesis. The concept is that by coating the recycled aggregate many of the surface pores will be filled, which could not only control the workability but also could positively influence the compressive strength of the concrete.

2.2.3. **Density of recycled concrete aggregate**

In Figueiredo’s study as cited in Matias et al. (2013), he concluded that the RA density is predicted to be lower than that of the NA, since the cement paste in the RA has a lower density than the NA. Therefore, mortar is responsible for lowering the RAC density especially when increasing the amount of RA. Also, in Bravo et al. (2015) it was concluded that the use of RA causes a decrease in concrete's density, which reached values between 4.7% and 7.7% for full replacement of RA. Specific gravity and bulk density are comparative to concrete made with NA. This is mostly due to the high-water absorption rate of the RCA, as the mortar has higher porosity than aggregates; hence RCA absorbs more water than NA (Yehia et al., 2015).

2.2.4. Compressive strength

Concrete's mechanical properties are adversely affected by using recycled and by-product materials as substances, especially compressive strength and modulus of elasticity, yet the reduction in these properties may be countered to some degree by pre-treating these substances (West, 2015, Dhir et al., 2019a). Replacing 50% to 100% of NA with RA decreases the compressive strength by 5% to 25%. However, up to 30% of NA can be substituted with coarse RCA without any effects on concrete strength. Strength gain for RCA is lower than normal NA concrete (Figure 2.16) (Yehia et al., 2015, Velay-Lizancos et al., 2018).

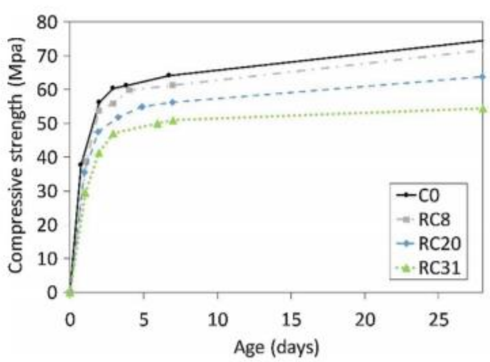


Figure 2.16 Compressive strength at early ages and at 28 days (Velay-Lizancos et al., 2018)

Table 2.7 shows the mix proportions for their recycled mix, in which they only replaced the normal 4-12 mm aggregates with the recycled aggregates. There was no pre-treatment of the recycled concrete aggregates in their approach. However, the paper described the process of mixing as following:

1. Moisten the mixer with a wet cloth.

2. Add natural sand and mix for 30 s.

3. Add cement and mix for 60 s.

4. Add coarse natural aggregate and recycled aggregate and mix for 60 s.

5. Without stopping the mixer, add water slowly for 30 s and mix for 60 s.

6. Without stopping the mixer, add the superplasticizer slowly for 30 s and mix the necessary time until the power consumed by the mixer is stabilised stabilized

As the water cement ratio is fixed, the study did mention adding a superplasticizer even though it is not mentioned in Table 2.7.

Table 2.7 Mixtures of concrete (Velay-Lizancos et al., 2018)

Material	C0	RC8	RC20	RC31
CEM I 52.2 R-SR 3 [Kg]	400	400	400	400
Recycled aggregate 0/12 (RA-0/12) [Kg]	–	145	363	563
Natural sand 0/2 (NA-0/2) [Kg]	308	308	308	308
Natural sand 0/5 (NA-0/5) [Kg]	608	539	437	343
Coarse Natural aggregate 4/12 (NA-4/12) [Kg]	300	223	108	2
Coarse Natural aggregate 10/20 (NA-10/20) [Kg]	600	600	600	600
Effective water/cement ratio	0.45	0.45	0.45	0.45
Total volume (liters)	1020	1028	1040	1052

Furthermore, Rahal (2007) illustrated that concrete with 100% replacement of recycled aggregates and a lower w/c ratio than normal concrete may have a higher compressive strength, yet it is less workable. However, if the w/c ratio is adjusted to maintain workability then it is expected that the compressive strength of the RCA will be lower. Rahal (2007) increased the amount of cement to compensate for the loss of strength (Table 2.8).

Table 2.8 Concrete mix proportions (Rahal, 2007)

Class	K200	K250	K300	K400	K500
Target 28-day cube strength (MPa)	20	25	30	40	50
Cement (Type I)	360	380	400	420	460
Water (+liquid super plasticizer)	234	190	192	181	184
w/c	0.65	0.50	0.48	0.43	0.40
Natural sand	705	705	705	705	705
Coarse aggregate (9 mm)	500	500	500	500	500
Coarse aggregate (12 mm)	340	340	340	340	340
Coarse aggregate (19 mm)	260	260	260	260	260

Wang et al. (2013) suggested that a good RCA is achieved by using a fine pozzolanic material as a replacement for part of the cement. Not only did he suggest the addition of the materials, but he also proposed a new mixing scheme the "W3T4" method which is illustrated in Figure 2.17. The differences between "W3T4" and other mixing methods are:

- The superfine powder was mixed at the first stage before adding water, noting that the pozzolanic powder is added to occupy the pores and cracks instead of water
- There is a high range water reducer, a high concentrate naphthalene-based superplasticizer, also named Naphthalene Sulfonate Formaldehyde Condensate (FDN) was added at the first stage also, and this way the superplasticizer will blend uniformly with the superfine powder. Thus, a new and much denser ITZ was formed.

The pre-wetting procedure of RCA is very important, to control the humidity condition of RCA. Water (W2) was used during the second stage of mixing to form a thin layer with low water-cement ratio slurry on the surface of RCA.

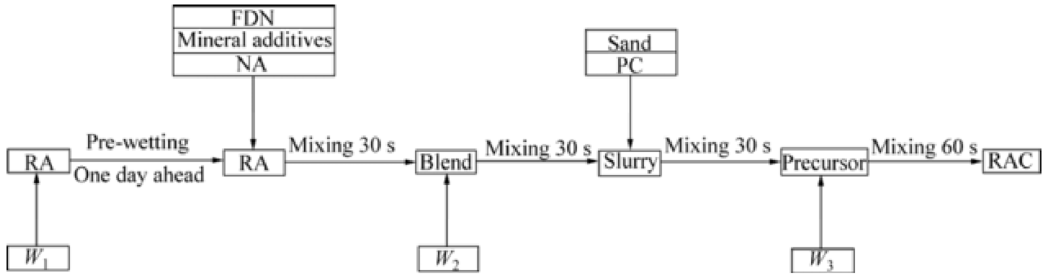


Figure 2.17 Procedure of "W3T4" method for producing RCA (Wang et al., 2013)

Scholars working with recycled materials in concrete often mention the process of mixing the recycled constituents to form concrete, and this process varies slightly in different papers. This research will investigate the effect of changing the process of mixing these recycled materials and will suggest a novel process that counters the loss of compressive strength and workability without the usage of a superplasticizer. Finally, when using recycled aggregates in concrete, a decrease in strength is expected compared to that made of normal aggregates (Beltrán et al., 2014, Kou and Poon, 2015, Velay-Lizancos et al., 2018, Thomas et al., 2018).

This research will suggest a process involving a pre-treatment method to control the loss of compressive strength in recycled concrete.

2.2.5. Flexural strength and splitting tensile strength.

RCA has a marginal effect on flexural strength, where research showed that the decrease in flexural strength is limited to 10% (Xie et al., 2015). Also RCA in other cases showed that it has a similar flexural behaviour with NA (Yehia et al., 2015). On the other hand, a reduction of up to 10 % in split tensile strength was observed when virgin aggregate was substituted with recycled aggregate. Studies also suggest that split tensile strength is more dependent on the binder quality rather than the aggregate type (Ajdukiewicz and Kliszczewicz, 2002, Etxeberria et al., 2007, Xie et al., 2015).

2.2.6. **Modulus of elasticity.**

The modulus of elasticity is an important mechanical property which indicates the stiffness of concrete. However, concrete is affected by so many parameters such as porosity of the aggregate and matrix, the dense nature of the aggregate and the transition zone characteristics of the aggregates (Thomas and Gupta, 2013, Thomas et al., 2013a, Thomas et al., 2013b). In more detail, the aggregate's porosity and density determines the stiffness of the bulk matrix. Therefore, the replacement of NA with RA also affects the modulus of elasticity (Figure 2.18) (Thomas et al., 2018). Furthermore, RCA content has a more noticeable effect on the modulus of elasticity than that of compressive strength due to its porous nature, low density and weak bond between old ITZ and new ITZ due to presence of more capillary voids and cracks (Bravo et al., 2015, Thomas et al., 2018).

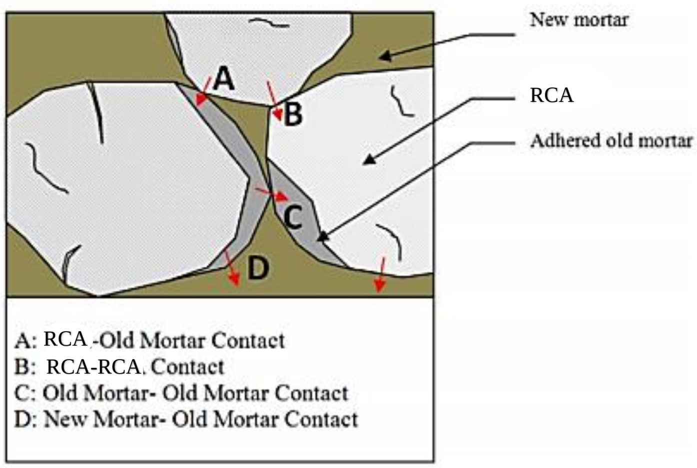


Figure 2.18 Load transfer mechanism in RCA concrete (Thomas et al., 2018)

Thomas et al. (2018) stated that the recycled concrete aggregates were pre-wetted to the saturated surface dry condition before mixing where the quantity of mixing water was determined after applying corrections for extra moisture. Yet, he did not mention cleaning RCA of not from dust and quarry powder before usage. Yehia et al. (2015) stated that the modulus of elasticity in some cases is reduced by 45% of the modulus of elasticity of normal concrete. Moreover, this percentage of reduction in the modulus of elasticity differs based on the percentage of RA replacement. In detail, the 45% reduction was found at 100% replacement of NA with RA, while up to 15% reduction was observed at 30% replacement of NA with RA. Figure 2.19 from Velay-Lizancos et al. (2018) illustrates a decrease in the elastic modules with the increase of the amount of recycled concrete aggregates in the mix shown in Table 2.6 in section 2.2.5.

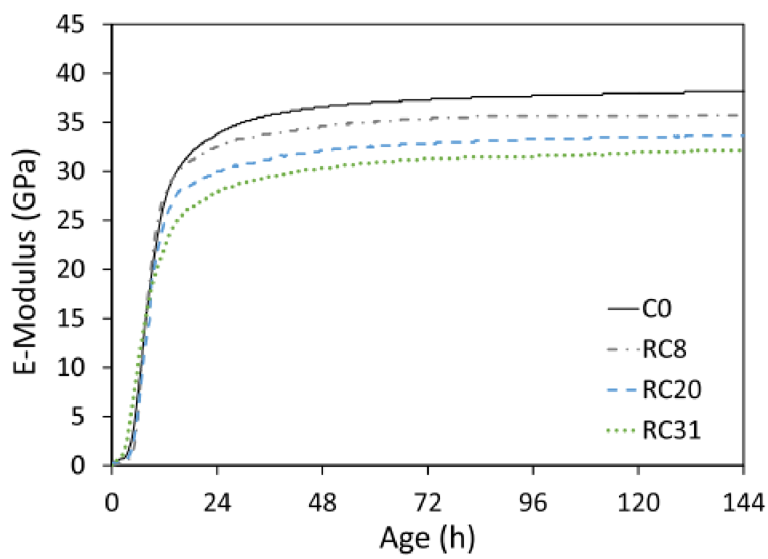


Figure 2.19 Elastic modulus at early ages (Velay-Lizancos et al., 2018)

Elastic modulus results will be further investigated in this research using a high sensitivity extensometer, which will give a reliable result on the elastic modulus of recycled concrete aggregates before and after suggested pre-treatment.

2.2.7. **Water/cement ratio adjustment**

The drop in compressive strength in RCA concrete can be compensated for by controlling the water/cement (w/c) ratio. Figure 2.20 displays the relationship between the compressive strength of the RCA and control concrete samples of three experimental phases of 28, 180 and 360 days of age and the effect of the w/c ratio on them. The results indicate that there are no momentous changes comparing to the control mix when using 20% RCA. Yet, when the substitution of the aggregates is 100%, there is a significant loss of compressive strength. So, it is necessary to reduce the w/c ratio to ensure similar levels of strength (Thomas et al., 2013b, Thomas et al., 2018).

This procedure is to counter the water absorption levels of RCA mentioned earlier in point 2.2.3. Water is added to maintain workability however strength is usually decreased due to the extra water used. This thesis proposes not to adjust the water cement ratio. Instead it will be proposed to coat RCA with silica fume which will seal the pores on the surface, which will mitigate the loss of workability without adjusting the w/c ratio.

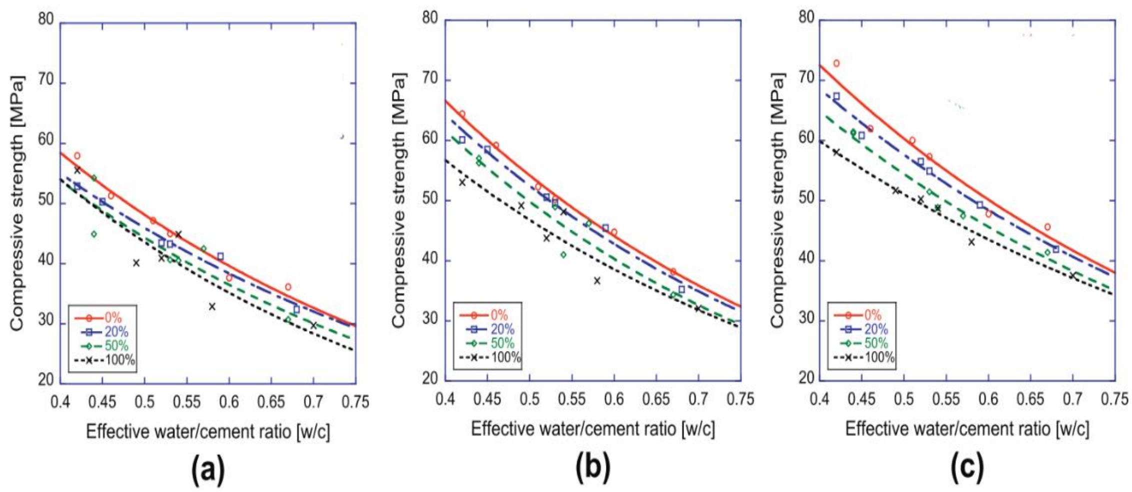


Figure 2.20 The relationship between compressive strength and water/cement ratio of different degrees of substitution after 28 days (a), 180 days (b) and 365 days (c) (Thomas et al., 2013).

2.2.8. Recycled concrete aggregates: Pre-treatment with silica fume

Bui et al. (2018) proposed a treatment method for RCA as shown in Figure 2.21. Firstly, the recycled aggregates are soaked in sodium silicate (Na_2SiO_3) solution for pre-treating and then coated with various percentages of silica fume. Sodium silicate will penetrate the RCA structure to seal cracks and react with portlandite (calcium hydroxide $Ca(OH)_2$-CH crystals) of RCA to make a stronger C-S-H (calcium silicate hydrate ($CaO.SiO_2H_2O$) product in concrete as in the following reaction:

$Na_2SiO_3 + Ca(OH)_2 + H_2O \rightarrow CaO.SiO_2.H_2O + NaOH$ (1)

Sodium silicate is a commercial product that is used to activate pozzolans (McDonald and Thompson, 2006). Sodium silicate is also used as an activator in geopolymer concrete (Singh et al., 2015). Furthermore, sodium silicate can reduce the water absorption coefficient of RCA. Furthermore, silica fume can fill in pores and cracks of RCA and convert CH crystals into C-S-H gel (Kou et al., 2011, Spaeth and Tegguer, 2013, Sasanipour and Aslani, 2019, Guo et al., 2020).

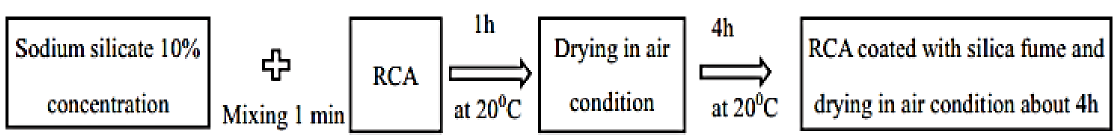


Figure 2.21 Pre-treating process for RCA with sodium silicate and silica fume

This research suggests a new process for coating RCA with silica fume, in includes draying the aggregates before coating and wating 28 day after coating for silica fume to set.

2.3. Silica fume

Silica fume (SF) is an industrial by-product from silicon and ferrosilicon production process. Table 2.9 shows typical SF chemical components (Nežerka et al., 2019).

Table 2.9 Chemical composition of PC and SF (Nežerka et al., 2019)

	PC	SF
	wt% (±0.5%)	
CaO	64.2	1.50
SiO_2	19.5	92.1
Al_2O_3	4.70	0.00
Fe_2O_3	3.20	0.41
SO_3	3.20	0.00
MgO	1.30	0.30
K_2O	0.78	0.69
TiO_2	0.00	0.00
LOI	3.20	5.00

Silica fume is an ultrafine reactive mineral admixture with spherical particles less than 1 μm in diameter. It reacts with the calcium hydroxide which is produced during Portland cement hydration. SF addition to cement improves the compressive strength of concrete where it is used for producing high strength to ultrahigh strength concrete (Chandra and Berntsson, 1996, Guo et al., 2020, Khan, 2018, Khan and Ali, 2019). Even though it is known that the performance of concrete depends firstly on the quality of aggregates, yet the properties of the cementitious material, and the ITZ between them is also vital (Nežerka et al., 2019). The ITZ is the weakest link in this chain, mostly in terms of fracture behaviour, which is due to the fact that the first cracks usually appear in the vicinity of recycled aggregates because of the excessive loading (Hsu et al., 1963, Guinea et al., 2002, Akçaoğlu et al., 2005). Moreover, Nežerka et al. (2019) concluded that replacing 10–20% of Portland cement with silica fume improves the ITZ around recycled aggregates and produces concrete with superior strength.

Knowing this means that silica fume as a paste could be used as a coating material for the recycled concrete aggregate and this research will be investigating this to explore the timing of the addition of silica fume to the mix.

2.3.1. **Alkali–silica reaction**

Alkali–silica reaction (ASR) is a reaction between the alkaline pore solution of concrete and various metastable forms of silica (Rajabipour et al., 2015). This change in the chemical composition of the alkali–silica gel in mortars as dosages of lithium hydroxide LiOH, which will be considered as a GGBS activator, and lithium carbonate Li_2CO_3 increased, leads to gels with a lower CaO/SiO_2 ratio. Moreover, silica appeared to react with lithium preferentially over other alkali species (Kawamura and Fuwa, 2003, Mo, 2005).

Kawamura and Fuwa (2003) concluded that the threshold dosage of Li + ion for both LiOH and Li_2CO_3 was about 0.75 % in mortars made with a high-alkali cement. This affects the lithium salts on ASR gel composition, where the average CaO/SiO_2 ratio decreases with increasing the amount of lithium. It was also found that the composition of ASR gels became homogeneous at a high dosage level of lithium. Guo et al. (2019) added that the dissolved silica will first react with the lithium content, and the Li-Si phase can be formed on the fused silica surface. The alkali-silica reaction will then be inhibited after the formation of the Li-Si phase. The generated Li-Si phase has an amorphous structure as no apparent crystalline peaks can be observed. Kim and Olek (2014) confirmed that the dissolved silica will first react with the calcium contents to form the CSH gel while the ASR gel can only be generated after all the $Ca(OH)_2$ phase is consumed. Moreover, Hou et al. (2004) confirmed this and concluded that this reaction sequence is very similar to the pozzolanic reaction in terms of forming more polymerized C-S-H by consuming reactive silica and calcium. Collins et al. (2004) illustrated that in the presence of LiOH, dissolved Si in solution was found to increase with an increase in Li, while the opposite trend was apparent for those samples prepared with LiCl. The increase in OH, contributed to the solution by LiOH, increases the rate of dissolution of silica in the solution. Another potential explanation is that more silicate reaction product is formed with an increase in Li.

2.4. **Lithium**

Recycling electronic waste to recover raw materials is a valuable approach to saving the environment. Electronic devices containing expensive metals such as lithium-ion batteries, which use lithium as the electro-active materials (Jo and Myung, 2019). The demand for clean energy has significantly expanded the use of lithium-ion batteries (LIB) from applications such as small portable electronic devices all the way to electric vehicles (Whittingham, 2004, Padhi et al., 1997). There is no shortage of lithium, however, there is shortage of highly pure lithium carbonate and lithium hydroxide (Narins, 2017, Pagliaro and Meneguzzo, 2019). there are no papers in evidence which consider the use of Li as a GGBS/SF activator and this thesis will conciser this novelty.

2.4.1. **Lithium recycling**

The process used to obtain lithium requires less energy, and less environmental impact compared to the extraction of it (Sanghai et al., 2019). Most of the lithium resources for LIB are extracted from brine lakes which contain 66% of all lithium. Furthermore, there are many efforts to recycle metals from LIB, and recycled raw materials are regularly reapplied in new battery products (Figure 2.22) (Jo and Myung, 2019).

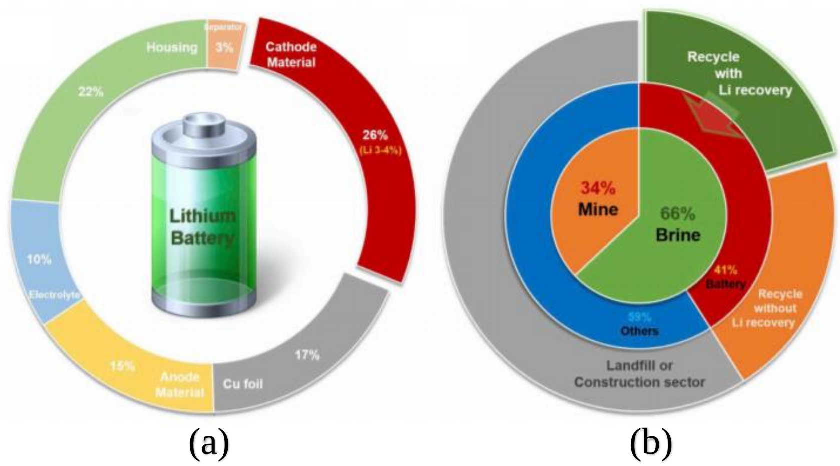


Figure 2.22 (a) Components of conventional lithium batteries (%).
(b) Circulation of lithium resources. (Jo and Myung, 2019)

The recycling process in depth: the spent batteries are first discharged and then manually dismantled to recover the Al and Cu foils in metallic form and the separator, and then recycled after dismantling (Figure 2.23) (Pagliaro and Meneguzzo, 2019).

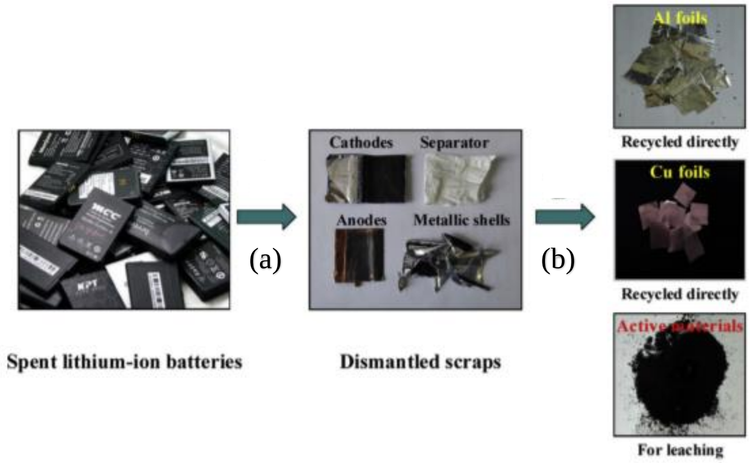


Figure 2.23 . Simplified pre-treatment process of spent LIB based on citric aicd/hydrogen peroxide oxidative leaching of Co and Li: (a) manual dismantling; (a) peeling off Al/Cu foils and recycling of Al and Cu (Pagliaro and Meneguzzo, 2019).

2.5. Ground granulated blast-furnace slag

Ground granulated blast furnace slag (GGBS) is a by-product of the iron industry, when heating the iron to about 1500 °C a molten slag floats above the molten iron. Table 2.10 displays the chemical composition of GGBS. Cooling molten iron slag with water produces a glassy granulate, which is dried and then ground to the required size, to be known as ground granulated blast furnace slag. (Tsai et al., 2014, West, 2015, Korde et al., 2019).

Table 2.10 Chemical composition of GGBS and PC (Tsai et al., 2014)

Chemical composition (wt.%)	GGBS	Cement
SiO_2	33.42	21.04
Al_2O_3	13.35	5.46
Fe_2O_3	0.21	2.98
CaO	41.16	63.56
MgO	7.76	2.52
SO_3	N/A	N/A
MnO	N/A	N/A
Others	4.10	4.44
Free-CaO	0.1	0.72

It has a composition of 30% to 40% silicon dioxide (SiO_2) and approximately 40% CaO, which is less than the chemical composition of Portland cement (PC). GGBS is more environmentally friendly than Portland cement as its carbon footprint (circa 35kg/m3) is considerably lower than PC (circa 800kg/m3). The production of GGBS results in a release of up to 80% less CO_2 emissions than the emissions of CO_2 in PC (Roy, 1982, U et al., 2016). It has a better water impermeability and high resistance to corrosion caused by chloride ingress and sulphate attack. Although GGBS has a longer setting time, this can be an advantage because the concrete stays workable for a longer period and it reduces the risk of early thermal cracking (Arivalagan, 2014, Samson et al., 2017, Saranya et al., 2018, Korde et al., 2019, Korde et al., 2020).

2.5.1. Influence of GGBS on the workability

Concrete's workability increases with an increase of GGBS, where maximum workability is found at about 40% GGBS replacement (Hirde and Gorse, 2015). The narrower the GGBS's particle size distribution the better the workability of the concrete. Although the workability is correlated with the particle size and smoothness, yet the influence of GGBS's particles shape is not remarkable due to their similar particle size (Wan et al., 2004).

2.5.2. GGBS effect on compressive strength

It takes time for the compounds in GGBS to react with water and obtain its hydroxyl ions whereby the hydration products of Portland cement break down the glassy slag parcels at an early age (Cheng et al., 2005, Langer, 2018). Table 2.11 shows a mix examined by Cheng et al. (2005) to examine compressive strength behaviour when replacing cement with GGBS.

Table 2.11 Concrete mixes conducted by (Cheng et al. 2005)

Mix	Water	Cement	Slag	Fine aggregate	Coarse aggregate
A	235	427	0	780	843
B	235	256	171	761	843
C	235	171	256	752	843

Figure 2.24 illustrates that the compressive strength of concrete made with a partial replacement of Portland cement with GGBS can be higher than concrete made with ordinary Portland cement, especially after GGBS's hydration (pozzolanic reaction) is nearly accomplished.

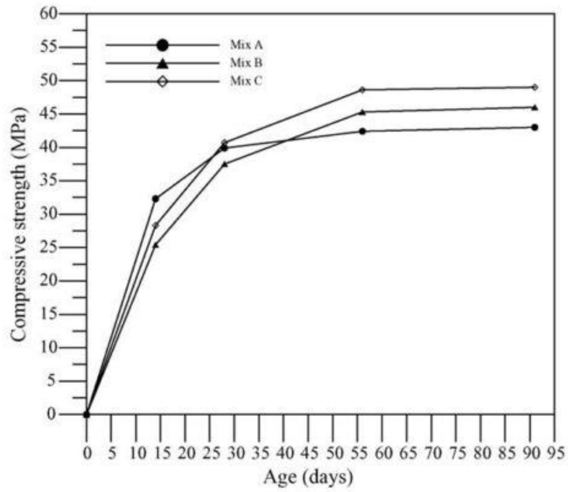


Figure 2.24 Compressive strength development curves for GGBS mixes (Cheng et al. 2005)

Korde et al. (2019) substituted up to 70% of Portland cement with GGBS and enhanced early age strength using a novel chloride free GGBS activator, a commercial accelerating admixture and by controlling the temperature. Table 2.12 displays the mix proportions. The 70% GGBS compressive strength results are displayed in Figure 2.25.

Table 2.12 GGBS mix properties (Korde et al., 2019)

Mix Proportions (per m^3)		Cementitious Materials Proportions		
Material	Mass (kg)	% GGBS	Cement (kg)	GGBS (kg)
Fine Aggregate	1758	0	586	0
Cementitious Materials	586	30	410.2	175.8
Water (w/c = 0.5)	293	50	293	293
Admixture (1% binder)	0 or 5.86	70	175.8	410.2

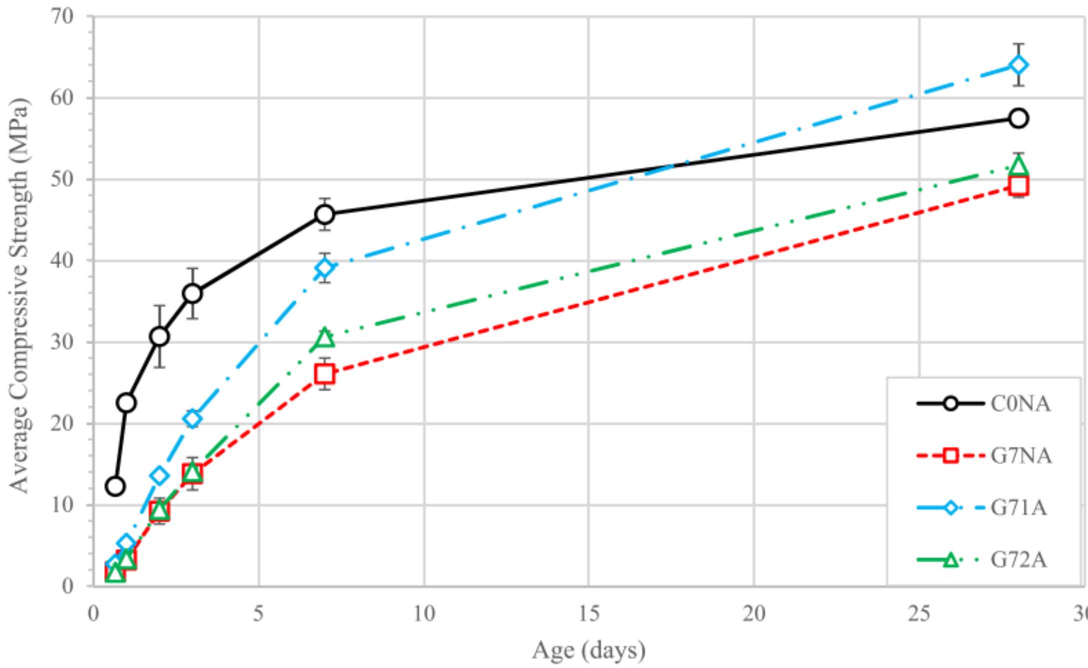


Figure 2.25 Relationship between CEM I 42.5 R and GGBS compressive strengths and age with and without admixtures for 70% slag at ambient temperature 0 = PC, 7 = 70% GGBS, NA = no admixture, 1A = new admixture, 2A=proprietary admixture (Korde et al., 2019).

With 70% GGBS and Admixture (1), the compressive strength development of the GGBS samples are considerably higher than without admixture or with (2). The main conclusion is that it is possible to achieve the equivalent early age strength of PC (Korde et al., 2019).

This research will replace 100% of the Portland cement and use 80% GGBS and 20% silica fume and will suggest a novel recycled Lithium-based activator to attain 28 days compressive strength as normal concrete without using temperature as an activator.

2.5.3. GGBS alkaline activators

GGBS is a slow reacting cementitious material, which can achieve a higher compressive strength when an alkaline activator is added to it. Kim et al. (2011) classified alkaline activators into six groups:

- Caustic alkalis
- Non-silicate weak acid salts
- Silicates
- Aluminates
- Aluminosilicates
- Non-silicate strong acid salts

Of these activators, NaOH, Na_2CO_3, $Na_2O\_nSiO_2$ and Na_2SO_4 are the most widely available and economical chemicals in the market. Although GGBS on its own does react with water without an activator, the hydration rate is very slow and impractical for site use in the absence of either Portland cement or an activator. Moreover, reaction is also enhanced by thermal activation (Kim et al., 2011, Rajesh et al., 2013).

Rajesh et al. (2013) in their study compared sodium silicate (Na_2SiO_3), sodium carbonate (Na_2CO_3) and sodium hydroxide (NaOH) as alkali activators for GGBS. They concluded that GGBS activated with sodium silicate sets rapidly, with a higher Na_2O dosage, consequentially a shorter setting time. Furthermore, of these three activators that they examined, NaOH is best; Na_2CO_3 was the second; Na_2SiO_3 was the third in terms of flexural strength. Also, the compressive strength growth rate of an alkali activated GGBS mix in early age is high when compared to normal concrete made with Portland cement.

The use of GGBS to replace Portland cement also increases the chloride binding capacity of the concrete. This is credited to their high alumina content. Chloride in concrete exists as free a chloride dissolved in the pore water, or as a bound chloride. The bound chlorides are either chemically bound to the tricalcium aluminate (C_3A) and the calcium aluminoferrite (C_4AF) or physically bound to the surface of the hydration products C-S-H gel (Hussain and Al-Saadoun, 1993, Ogirigbo and Black, 2015, Bondar et al., 2019, Song et al., 2020, Chang et al., 2020).

This research will investigate using lithium hydroxide and lithium chloride as recycled alkaline activators for GGBS and silica fume.

2.5.4. **GGBS and bleeding capacity**

Wainwright and Rey (2000) defined bleeding capacity as: "the fraction of the initial volume of the concrete that has separated out as bleed water during the entire course of the test", where they defined bleeding rate as the volume of water collected per second during the first 40 min of the test. "It is expressed in ml/ cm^2 of exposed surface". In addition, Figure 2.26 shows that partial replacement of cement with 55% of GGBS obtained from four different locations, increased the bleed capacity by 30% compared to ordinary Portland cement, but it only had a slight effect on the bleeding rate. However, increasing the GGBS level up to 85% had no further effect on bleeding (Tsai et al., 2014).

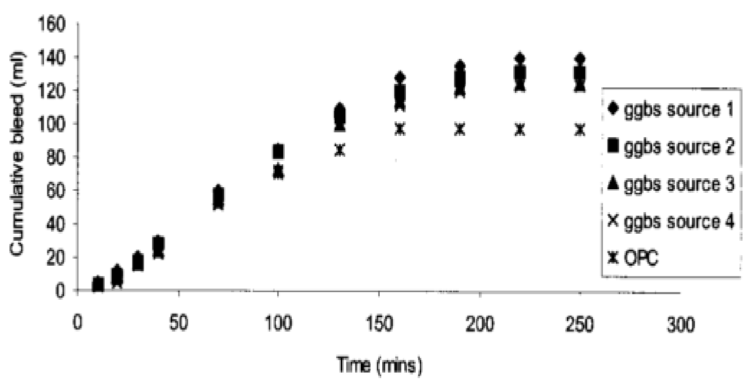


Figure 2.26 Bleed time curves for 55% GGBS concrete mixes (Wainwright and Rey, 2000).

2.6. **Rainwater harvesting**

With increasing surface runoff flooding due to the vast urbanization contribution, rainwater harvesting is one of the best available methods for creating sustainable water cycles in urban developments (Lee et al., 2012). Furthermore, Martin et al. (2015) states that rainwater harvesting systems have two main elements:

- A catchment area to collect the rainfall.
- A large vessel that holds the harvested rainwater until it is called upon.

According to Chong et al., as cited by Leong et al. (2017), a successful rainwater harvesting system involves gathering data on the physical, chemical, and microbiological characteristics of rainwater in order to minimise health risks from rainwater reuse and to design an effective water treatment system. Moreover, Leong et al. (2017) concluded that regular cleaning of roofs and gutters is necessary for rainwater harvesting systems to diminish health risks from rainwater reuse. O'Hogain et al. (2011) conducted a pilot study on rainwater harvesting in Ireland, where all results were obtained without any use of first flush devices or any form of disinfection. They illustrated that the physicochemical results complied with the drinking water regulations over the sampling period, except for ammonia. Table 2.13 shows results for the harvested rainwater compared with the S.I.278 (European Communities Drinking Water Regulations) and S.I.155 (European Communities Quality of Bathing Water Regulations).

If the location of the rainwater harvesting system has a considerable number of birds, fecal materials from birds are usually present on the roof. That could probably be solved by increasing the size of the first-flush device. Alternatively, other measures, such as chlorination or UV radiation, should be applied if the harvested rainwater is to be used as potable water (Gikas and Tsihrintzis, 2017).

Table 2.13 Overall physicochemical results for the harvested rainwater based on 14 monthly samples taken between January 2006 and January 2007 (O'Hogain et al., 2012)

Parameter	Units	Mean	Min	Max	SD	Median	Drinking water guideline	Bathing water guideline
Chloride	mg/L	3.83	<0.01	27.83	7.37	1.49	250 mg/L	
Nitrate as NO_3	mg/L	1.23	<0.01	2.84	0.92	1.20	50 mg/L	
Nitrite as NO_2	mg/L	0.04	<0.01	0.20	0.06	0.03	0.50 mg/L	
Sulphate	mg/L	3.35	<0.01	37.40	10.26	0.30	250 mg/L	
Ammonia as NH_3	mg/L	1.35	0.11	7.16	1.91	0.56	0.28 mg/L	
pH	pH units	7.07	6.67	7.83	0.31	6.98	6.5–9.5	6.0–9.0
TDS	mg/L	59.15	15.00	174.00	48.75	49.00		
TSS	mg/L	5.23	2.00	22.00	5.82	3.00		
Turbidity	NTU	0.63	<0.01	2.10	0.75	0.40	NAC and ATC	
Sodium	mg/L	2.62	<0.01	16.40	4.33	1.50	200 mg/L	
Calcium	mg/L	5.43	<0.01	46.80	12.89	1.40	None	
Lead, total	µg/L	3.28	<0.01	15.46	4.66	2.21	10 µg/L[a]	
Iron, total	µg/L	61.50	<0.01	271.12	66.98	57.75	200 µg/L	
Cadmium, total	µg/L	< 0.01	<0.01	<0.01	<0.01	<0.01	5.0 µg/L	

Note that Chloride levels are compatible with I.S.-EN-206 (chloride content is shown in Table 2.14)

Table 2.14 Maximum chloride content of concrete

Concrete use	Chloride content class[a]	Maximum Cl^- content by mass of cement[b]
Not containing any steel reinforcement or other embedded metal with the exception of corrosion-resisting lifting devices	Cl 1.0	1.0%
Containing steel reinforcement or other embedded metal	Cl 0.2	0.2%
	Cl 0.4	0.4%
Containing prestressing steel reinforcement	Cl 0.1	0.1%
	Cl 0.2	0.2%

2.6.1. **Catchment area**

The quality of catchment area is an important factor that effects the quality of the harvested rain water. Gikas and Tsihrintzis (2017) in their research investigated the quality of roof runoff water from two roofs made of standard construction materials, where the first one was made from ceramic tiles and the second one from concrete. They installed a rainwater collecting system on both roofs which included a first-flush device. Furthermore, the results showed that the quality of water in the collection tank is improved due to the removal of the first-flush water. Also, removing the first flush worked in relation to the physicochemical characteristics measured, as the average of these values, except for ammonium nitrogen, was below the limits set by the EU for drinking water.

However, they also concluded that the water from the tiled roof had remarkably higher concentration of Ammonium NH_4-N and statistically significantly lower calcium Ca2+ concentration compared to that of the concrete roof. Finally, metal roofs are commonly recommended for rainwater harvesting applications. However, they did not produce significantly greater harvested rainwater in terms of quality when compared to the other roofing materials. Moreover, concrete tile and cool roofs also appear to be good candidates for rainwater harvesting catchments, given the overall similarity in harvested rainwater quality among these materials (Mendez et al., 2011).

This research will investigate using harvested rainwater with a 100% replacement of normal tap water to in a concrete mix.

2.7. **Particle packing**

Determination of concrete mixture constituents is one of the most important factors affecting the quality of concrete. It is possible to obtain a greater strength and quality in concrete with better packing of the different sized and shaped particles. In a concrete mix it is required to get an in-depth understanding of aggregates characteristics such as shape and size. The performance of concrete is significantly affected by the degree of packing of its aggregates. Thus, one needs an understanding of the concept of particle packing and its influence on concrete performance. The properties of aggregates have a significant role in determining the strength of concrete as the aggregate represents most of the concrete`s volume. Aggregate is the main portion in forming the concrete. Appropriate aggregate blend characteristics are important to guarantee good concrete mixture performance (Miao et al., 2018). Particle packing models are about selecting the proper sizes and proportions to fill voids. The smaller the particles the smaller the voids they contain, which are filled with smaller particles and so on. Kumar and Santhanam (2003) demonstrated that research on particle packing involves selection of appropriates sizes and proportions of aggregate, to get a suitable combination for optimal packing and that is to:

- Understand how a specified combination of particles packed in a system works
- Develop mathematical models for calculating packing densities and porosities

The characterization of aggregate packing in concrete is not an easy task. Aggregate structure is a complex system, moreover packing aggregates can be affected by several properties such as the aggregate particle size distributions and shape (Shen and Yu, 2011).

The Solid Suspension Model (SSM) was developed by Larrard (1989) a new enhanced method to the Equations of the Linear Packing Density Model (LPDM) developed by Mooney (1951). Furthermore, de Larrard and Sedran (1994) stated that "LPDM has shown good performances in predicting optimal proportions of cement pastes, mortars and concretes. But it suffered from an original defect, owing to its linear nature: curves giving relationships between packing density and proportions exhibit angular points in the vicinity of optimal values. Such a feature does not appear in practice" (Figure2.27). However, this is a valuable tool to optimize high packing density for cementitious materials but not for aggregate packing.

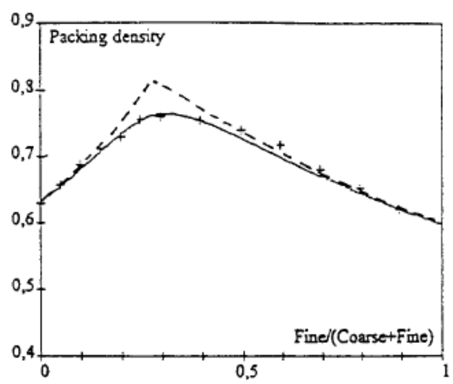


Figure 2.27 Packing density versus fine grains. Solid line: LPDM, dotted line: SSM (de Larrard and Sedran, 1994)

On the other hand, Popovics (1992), worked on packing in regards to the shape of aggregates particles. He mentioned that it is irregular from a geometric standpoint, therefore it cannot be defined, or measured, effectively in its influence on the properties of concrete. He mentioned a method that utilizes trilinear, triangular diagrams for the graphical presentation of grading displayed in Figure 2.28. This method is suitable primarily for the case when the aggregate is made up of three size fractions. This is an equivalent of grading curves made up of only two intermediate points between the minimum and maximum particle size.

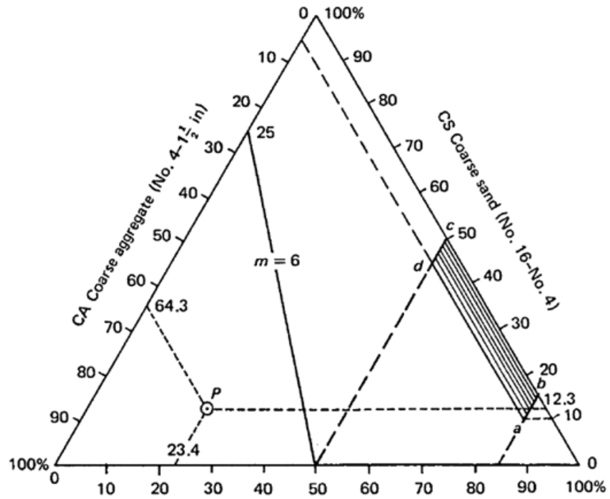


Figure 2.28 Grading representation in triangular diagram (Popovics, 1992).

Although some scholars approached aggregate particle packing as single sized and multiple sized spheres (Figure 2.29) like Mcgeary (1961), Kolbuszewski and Frederick (1963) and Mueller (2005). Yet, real aggregates are very much different from this model. Aggregates are irregular in shape and size (Abdel-Jawad and Abdullah, 2002).

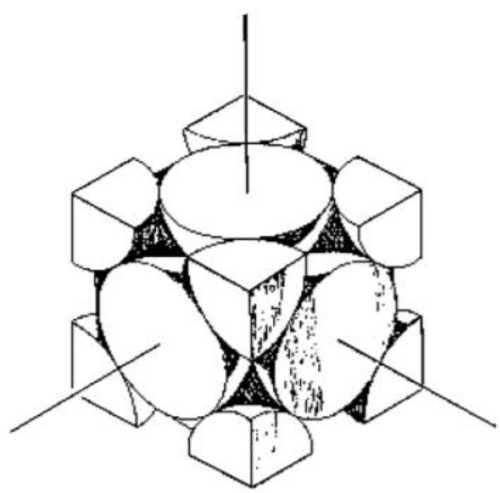


Figure 2.29 Maximum density arrangement of equal diameter spheres (Abdel-Jawad and Abdullah, 2002).

Dewar (2002) simplified and explained the basic concept of the theory of particle package. He indicated that when two particles of different size are mixed together, the smaller particle will attempt to fill the voids between the larger particles (Figure 2.30). The main relevant properties shown in Table 2.15 are mean size, voids ratio and relative density (Dewar, 1983, Dewar, 2002, Lin et al., 2019). To understand the behaviour of any mixture of two sized particles three basic concepts are introduced by Dewar (1983);

- Only three parameters are needed to characterise any particle component (mean particle size, relative density, and voids ratio)
- The mixture can be studied by generating a void ratio diagram.
- The void ratio of the mixture is influenced by the void ratio of the components, particle interference and mean size ratio.

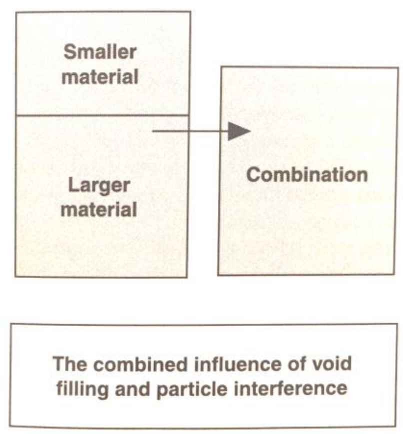


Figure 2.30 The basic principle of the Theory of Particle Mixtures (Dewar, 2002)

Table 2.15 Properties and test method

Property	Test method
Mean size	Grading
Relative density	Relative density (ssd)
Voids ratio	Bulk density (loose ssd)

2.7.1. **Mean size**

Average particle size is a more accurate characteristic of the fineness or coarseness of an aggregate than maximum or minimum size (Popovics, 1979, Dewar, 2002). Four measurements of average particle size were demonstrated by Popovics (1979); Arithmetic, Geometric, Harmonic and Logarithmic. The logarithmic basis was adopted by Dewar (1983).

The mean size of a single sized aggregated is calculated from

$$\log(mean\ size) = \frac{1}{2}[\log(upper\ size) - \log(lower\ size)] \quad (2)$$

For a graded material

$$\log(mean\ size) = \sum(fraction \times \log(mean\ size\ of\ the\ fraction) \quad (3)$$

r is the ratio of two adjacent materials (r value is always less than one)

$$r = \frac{mean\ size\ of\ the\ smaller\ material}{mean\ size\ of\ the\ larger\ material} \quad (4)$$

2.7.2. **Relative density**

The relative density of a saturated surface dried aggregate is compatible with the absorbed water and the internal air is considered part of the volume of the mass of the aggregate (Dewar, 1983, Dewar, 2002).

$$Relative\ density = (\frac{Mass}{Volume})/1000 \quad (5)$$

2.7.3. **Voids ratio**

It is necessary to take into consideration the medium in which the void ratio is to be measured. The voids ratio of an aggregate can be calculated from its density and relative density (Dewar, 1983, Dewar, 2002).

$$U = \frac{1000 \times Relative\ density}{Loose\ bulk\ density} - 1 \quad (6)$$

2.7.4. **Void ratio diagram**

The void ratio diagram is an important tool for understanding the process in the combination of particles. Figure 2.31 is an example of a theoretical voids ratio diagram demonstrating the effect of size ratio r on the resultant voids ratios of two materials with the same void ratio of 0.75 (Dewar, 1983, Dewar, 2002)

These following equations are needed to generate the void ratio diagram

void ratio for coarse aggregates

$$U_0" = (1 + U_0)(1 + mr)^3 - 1 \quad (7)$$

The fine particles usually occupy the available space within the matrix that is left between the coarse aggregates. Additional space needs to be modelled to compensate for the effect of particle interference of the fines with the coarse which is modelled as the notional volume (Dewar, 1983, Dewar, 2002). This was named the “wall and barrier effect” by Bache (1981). Consequently, Z is a function of the size ratio, r, and the void ratio U_0 of the coarser material which is called the notional width factor, Z.

$$Z = k_{int} + [(1 + U_0)^{\frac{1}{3}} - 1 - k_{int}]r^{kp} \quad (8)$$

Void ratio for fine aggregates

$$U_1" = \frac{(1+U_1)U_0^{"}}{(1+U_0^{"})-(1+Z)^3} - 1 \quad (9)$$

Fine aggregates to total solid material

$$n = \frac{U_0^{"}}{(1+U_1^{"}+U_0^{"})} \quad (10)$$

Void ratio at certain point

$$Un = nU1" \quad (11)$$

Void content at certain point

$$Vn = \frac{Un}{1+Un} \quad (12)$$

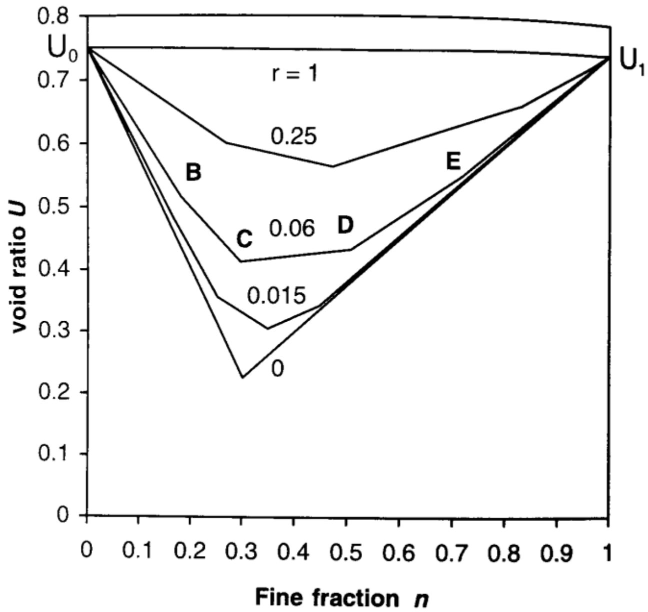


Figure 2.31 Voids ratio diagram of two materials with the same void ratio of 0.75 (Dewar, 2002)

To generate such a diagram the values of the spacing factors between the points for coarse and fine aggregates is given by Dewar (2002) shown in Table 2.16 and Figure 2.32. Furthermore, the values for empirical factors to determine Z the function of the size ratio is also given in Table 2.17.

Table 2.16 Values for spacing factors, m (Dewar, 2002)

Point in voids ratio diagram	**Spacing factor, m**
A (n=0)	0
B	0.3
C	0.75
D	3
E	7.5
F(n=1)	∞

Table 2.17 Values of empirical factors for determining Z (Dewar, 2002)

Point in voids ratio diagram	$\mathbf{k}_{int}$	$\mathbf{k}_{p}$
B	0.12	0.6
C	0.06	0.65
D	0.015	0.8
E	0	0.9

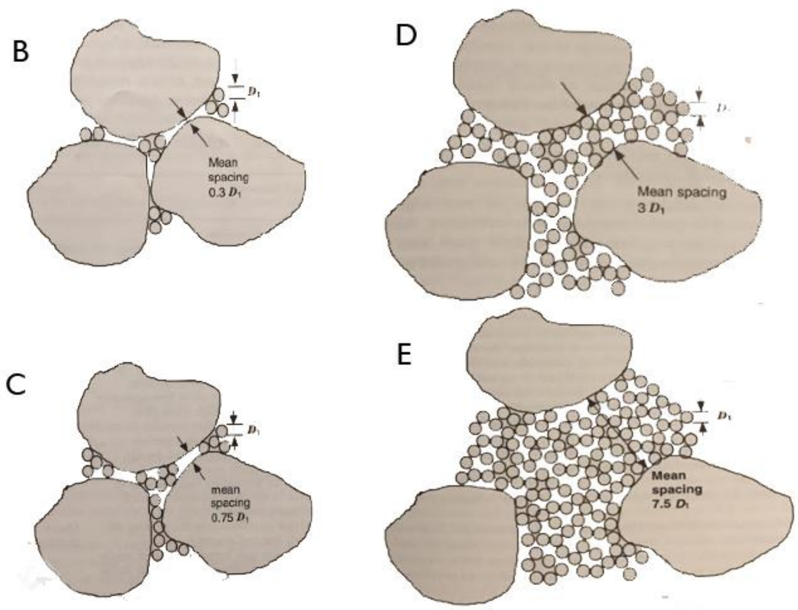


Figure 2.32 Spacing factors between the points for coarse and fine aggregates (Dewar, 2002)

This research will use the particle packing method to compensate for the strength loss when using recycled materials as concrete constituents.

2.8. Conclusion

This research review is to help the reader understand different aspects posed by research about replacing normal concrete constituents with recycled and by-product materials to pursue a sustainable concrete mix. There has been much research and discussion conducted around the partial replacement of these constituents and the effect on concrete's mechanical properties as a consequence. However, more research and testing are required to gain a better understanding of a 100% sustainable concrete mix that utilises solely recycled and by-product materials.

2.8.1. Significance and novelty

Rubber

This research suggests a pre-treatment method for chipped rubber with ultraviolet light may be effective in improving its properties and use on concrete, as this has not been tested in the concrete industry before. Another pre-treatment method is proposed by this study: using sulphuric acid to pre-treat chipped rubber before using it in a 100% replacement in a concrete mix. This study will measure the strength, elastic modulus, workability, and density of this concrete. This research will also suggest adding a waste material 6.3 mm aggregate to the treated chipped rubber and particle packing them. This will increase the strength of concrete made with chipped rubber which will enable the usage of it as a structural material.

Recycled concrete aggregates

A lot of research has been conducted on recycled aggregate, with many scholars suggesting the addition of a superplasticizer to control workability. This study will innovate on the process of coating the aggregate with silica fume by adding a drying stage of the recycled concrete aggregates before coating them with silica fume and waiting for them to harden/dry after coating them. Furthermore, it will suggest a technique of knowing the amount of silica fume used in coating based on the porosity of the recycled concrete aggregates. In this part recycled concrete aggregates will be segregated based on strength before being used in any mixes to quality control the recycled material.

GGBS and Silica fume

Research and industry use up to 75% of GGBS in PC concrete mixes, with and without silica fume. However, this research will use only GGBS and Silica fume as cementitious materials with 0% of Portland cement. The GGBS and Silica fume in this research will be activated by a new activator recycled from old lithium batteries. This research proposes lithium chloride and lithium hydroxide to be used as activators in a concrete mix with a 100% replacement of Portland cement. Strength, elastic modulus, density, and workability will be investigated.

Harvesting Rainwater for concrete

This research will implement rainwater harvesting techniques mentioned by previous research. but in this work, it is to be used in concrete as replacement of tap water. This work will suggest that if rainwater is harvested as mentioned above in the literature review it could be used in concrete without affecting its mechanical properties.

Combination

This work proposes that the combination of all these different recycled and by-product materials together into one mix requires testing, understanding, and testing each one individually and collectively. And then with the additional knowledge combine them more efficiently using particle packing theory.

This research project will identify a new way of making a novel concrete that is 100% sustainable and is solely produced out of waste, recycled and by-product materials and is mechanically viable to be used as a structural material.

Chapter 3

Materials and experimental methods

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3. Materials and experimental methods

The purpose of the study is to examine the impact of substituting normal concrete constituents with recycled and by-product materials. This study involves suggesting new pre-treatment methods, materials, and processes to mitigating the negative impact of using these recycled materials individually and collectively: ground granulated blast-furnace slag (GGBS), recycled concrete aggregate (RCA), recycled tyres in the form of chipped rubber, silica fume (SF), Lithium Chloride, Lithium Hydroxide recycled from old batteries and the 6.3 mm waste aggregates, on the concrete's mechanical properties. The primary parts of this chapter will include the rationale for the research and the descriptions of the research testing program, and the methodology (materials properties, tests, and instruments) that will be used in this study. A safety statement was compiled at the outset, regarding the handling and usage of hazardous materials as appropriate.

3.1. Rationale

The study will examine the impact of using the recycled and by-products as concrete constituents, on the mechanical properties of concrete (strength, elastic modulus, workability, and density). This will generate a set of data that will be used to compare with other research and will be used as milestones in the evolution of this research. This study will examine the usage of the following in a concrete mix to be considered and used as a structural material:

- Chipped rubber to replace normal aggregates.
- 6.3 mm waste aggregate as an improvement for particle packing.
- Recycled concrete aggregates, coarse and fine, to replace normal aggregates.
- GGBS and silica fume as cementitious materials to 100% replace Portland cement.
- Harvested rainwater to replace normal tap water.

This study will then propose a pre-treatment method that will mitigate the negative effects on the concrete properties (strength, elastic modulus, workability, and density) of using the listed materials as follows:

- Pre-treatment of chipped rubber by a) exposing them to ultraviolet light, b) or by submerging them into sulphuric acid to stiffen them and smooth their surfaces to get better workability and compressive strength.
- Using the 6.3 mm waste aggregate to make a better particle packed concrete, and then adding it with the same particle packing procedure to the pre-treated chipped rubber concrete for further improving the compressive strength of the rubberized concrete.
- Segregating recycled concrete aggregates based on strength, washing dust and quarry powder out of them, sieving them to the correct size, before coating them with silica fume with a suggested procedure to make a workable concrete that is as strong as normal concrete.
- Activating GGBS and silica fume with a new recycled material (lithium chloride and lithium hydroxide) to achieve a 28 day compressive strength as a normal cement would achieve.
- Filtrating harvested rainwater before using it in a concrete mix.

This research will combine all these materials with the acquired knowledge to design a fully recycled by-product concrete mix. The materials will be combined in two mixes: a) Chipped rubber-based mix, b) Recycled concrete aggregate-based mix. These two mixes are expected to be workable and have the required strength to be used in structural applications.

3.2. **Program**

To achieve the goals of this research, this program was divided to 5 phases which are displayed in Table 3.1 and Figure 3.1 and may be explained as follows:

- Preliminary Phase: this is where the reference mix was designed and the full testing procedure and instruments where tested. The reference mix was re-tested 5 times at the different stages for quality control and repeatability purposes.

- Trial Phase: this is where all materials are individually tested, and the data from the tests was compared to the data acquired from the literature review.
- Treatment Phase: this part tested suggested treatment processes, materials and methods on the recycled and by-product materials.
- Particle Packing Phase: in this stage the concrete's constituents where subject to particle packing before mixing,
- Combination Phase: this is where all these materials with the acquired knowledge to design a fully recycled by-product concrete mix are combined in 2 mixes. (one rubber based, and the other recycled concrete aggregate based)

Table 3.1 Phase matrix

<table>
<tr><th>Preliminary Phase</th><th>Trial Phase</th><th>Treatment Phase</th><th>Particle Packing Phase</th><th>Combination Phase</th></tr>
<tr><td rowspan="7">Reference mix</td><td rowspan="2">Rubber</td><td>UV light</td><td rowspan="3">Sulphuric rubber +
6.3 mm</td><td rowspan="3">Sulphuric rubber + 6.3 mm + GGBS and silica fume + rainwater
Particle packed</td></tr>
<tr><td>Sulphuric acid</td></tr>
<tr><td colspan="2">6.3mm</td></tr>
<tr><td>Recycled aggregate</td><td>silica fume coated</td><td rowspan="2">Particle packed</td><td rowspan="4">Coated recycled concrete aggregates coarse and fine + GGBS and silica fume + rainwater
Particle packed + Li</td></tr>
<tr><td>Recycled sand</td><td>silica fume treated</td></tr>
<tr><td>GGBS and silica fume</td><td>Activated with Lithium chloride
And Lithium hydroxide</td><td>Particle packed</td></tr>
<tr><td>Harvested rainwater</td><td>Filtered</td><td>Particle packed + 6.3 mm added</td></tr>
</table>

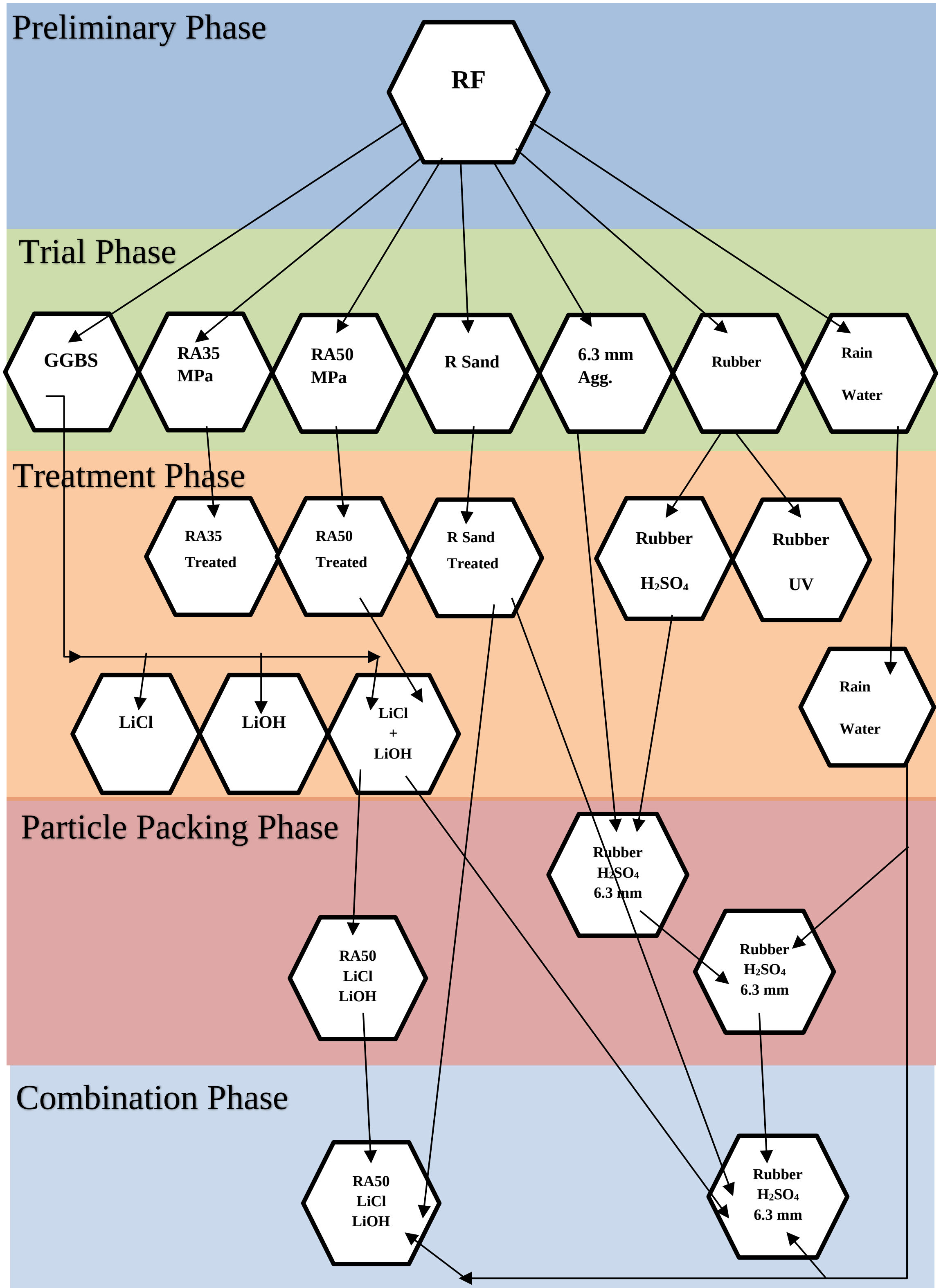


Figure 3.1 Mixing matrix

3.3. Materials

Table 3.2 lists all the materials used for all concrete mixes to conduct this study.

Table 3.2 Materials list

Materials
20 mm normal aggregates
10 mm normal aggregates
6.3 waste mm aggregate
20 mm recycled concrete aggregates 50MPa
10 mm recycled concrete aggregates 50MPa
20 mm recycled concrete aggregates 35MPa
10 mm recycled concrete aggregates 35MPa
Chipped rubber (recycled product)
Cement
Sand
Recycled Sand (recycled product)
Harvested rainwater
Sulfuric acid H_2SO_4
GGBS (by-product)
lithium hydroxide LiOH
lithium chloride LiCl
Silica fume (by-product)

3.3.1. Cement

This research project used Irish Cement bagged as a CEM II/A-L, components are illustrated in Table 3.3 .The product has been specifically designed to reduce the carbon intensity of cement production by replacing about 14% of clinker with ground limestone powder and to provide enhanced workability in block laying and plastering applications. The quality of all normal cement produced by Irish Cement is guaranteed to meet, in full, the requirements of Irish Standard I.S. EN 197-1 ‘Cement Part 1: Composition, Specifications and Conformity Criteria for Common Cements’, and the product is independently certified by the National Standards Authority of Ireland and is CE marked.

Table 3.3 Chemical and physical properties of CEM II/A-L from Irish Cement Ltd.

Property	%
SiO_2	16.68
Al_2O_3	4.48
Fe_2O_3	2.54
CaO	61.18
Cl	0.079
SO_3	3.01
F.CaO	1.59
LOI	8.6
Na_2O	0.54

3.3.2. **GGBS**

Ground Granulated Blast Furnace Slag (GGBS) used in this research was obtained from Ecocem GGBS which is produced by drying and grinding the GGBS at their milling plant in Dublin, manufactured to IS EN 15167-1. (https://www.ecocem.ie/products/ecocem-ggbs/)

3.3.3. **Aggregates**

Normal aggregates used in this thesis are produced at Roadstone Holding's limestone quarry, by means of blasting, crushing, and screening into the required sizes. Aggregates produced at their pit locations are extracted by excavator and screened/crushed into the required sizes: 10/14mm, 14/20mm and the waste aggregate 2/6.3mm. Production in the roadstone quarry is managed under the ISO 9001 quality management scheme with all locations having either System 2+ or 4 levels of attestation of conformity as appropriate in accordance with IS EN 12620 Aggregates for Concrete and IS EN 13139 Aggregates for Mortars.

3.3.4. **Recycled aggregates**

Recycled concrete aggregates were obtained by demolishing four concrete Kelly blocks that were caste for this project specifically to resemble a waste demolished building. Two of them had characteristic cube compressive strengths of 35MPa compressive strength at 28 days and the other two were 50MPa compressive strength at 28 days (Figure 3.2a). Kelly blocks were cored for compressive strength and density tests (Figure 3.2b).

(a) (b)

Figure 3.2 (a) Kelly blocks, (b) Concrete cores

These blocks were crushed via the same mechanism used to crush normal aggregate (Figure 3.3), that is to generate two batches of different strengths of waste concrete in the form of RCA.

Figure 3.3 Aggregate crushing machine

3.3.5. Silica fume

Micro silica used in this study was acquired from Elkem Microsilica: 920 EN is a dry silica fume powder certified to IS EN 13263 'Silica fume for concrete'. Table 3.4 is the data sheet provided by the supplier.

Table 3.4 Chemical and physical properties of Elkem Microsilica® 920 EN are regularly tested in accordance with EN 13263.

Property	*Unit*	*Value*
SiO_2	%	Minimum 85.0
SO_3	%	Maximum 2.0
Cl	%	Maximum 0.3
Free CaO	%	Maximum 1.0
Free Si	%	Maximum 0.4
Loss on ignition	%	Maximum 4.0
Specific surface area	m^2/g	Min. 15.0, Max. 35.0
Pozzolanic activity index	%	Minimum 100

3.3.6. Chipped rubber

Chipped rubber was obtained from a recycling car tyre centre, AES tyre recycling and remanufacturing facility, based in Co.Louth, which covers all aspects of the rubber tyre recycling process; from shredding, granulation and milling, to the production of saleable recycled products. Tyres are shredded down to 8-19 mm.

(https://www.aesirl.ie/business/tyre-recycling-remanufacturing/)

3.3.7. Sulphuric acid

Sulphuric acid used in this research was obtained from VWR chemicals (Figure 3.4)

Formula: H_2SO_4,

MW: 98.08 g/mol,

Boiling Pt: 330 °C (1013 hPa),

Melting Pt: 10,38 °C

Density: 1.84 g/cm³ (20 °C),

Storage Temperature: Ambient,

MDL Number: MFCD00064589,

CAS Number: 7664-93-9,

EINECS: 231-639-5,

UN: 1830, ADR: 8,II,

REACH: 01-2119458838-20,

Merck Index: 14,08974

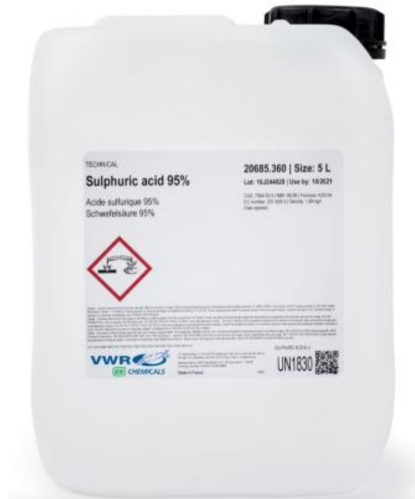


Figure 3.4 Sulphuric acid

3.3.8. **Lithium hydroxide**

Lithium hydroxide LiOH powder for this work was obtained from Alfa Aesar

Formula: $LiOH \cdot 1H_2O$,

MW: 41.96 g/mol,

Boiling Pt: 920 °C (1013 hPa),

Melting Pt: 462 °C

Density: 1.51 g/cm³ (20 °C),

Storage Temperature: Ambient,

MDL Number: MFCD00149772

CAS Number: 1310-66-3,

EINECS: 215-183-4,

UN: 2680, ADR: 8,II,

Merck Index: 13,05556

3.3.9. **Lithium chloride**

Lithium chloride LiCl powder for this work was obtained from Acros Organics

Formula: LiCl,

MW: 42.39 g/mol,

Boiling Pt: 1382 °C (1013 hPa)

Melting Pt: 614 °C,

Density: 2.07 g/cm³ (20 °C),

Storage Temperature: Ambient

MDL Number: MFCD00011078,

CAS Number: 7447-41-8

EINECS: 231-212-3,

Merck Index: 13,05550

3.4. **Equipment**

3.4.1. **Ultraviolet Fluorescent Tubes**

Type A ultraviolet 11- lamps were used and fitted to a wooden box 2 m x 2 m that has an isolated frame, where each lamp is power rated at 100 Watts, and the UV-A Radiation for each lamp is 100 Hr is 26.0 W (Figure 3.5).

Figure 3.5 Ultraviolet isolated frame

3.5. Experimental methods

3.5.1. Specimens casting and curing

For each mix, a total of 15 (300 mm x 150 mm) cylinders and 4 (100 mm x 100 mm) cubes were cast. The cubes were included to ensure independently that the two batches match in terms of their 28 days compressive strength. Five cylinders were tested respectively at 7, 28 and 56 days for strength and elastic modulus. Cubes were tested after 28 days for quality control.

3.5.2. Reference mix

A reference mix (C30/37) was designed as an S3 slump class concrete and was prepared with a water-to-cement ratio (W/C) of 0.5. All research mixes were compared with this base limestone mix in term of workability, density, elastic modulus, and compressive strength (Table 3.5).

708 kg/m3 -

Table 3.5 Reference mix

Material:	**Mass**	**Yield adjustment**
20mm aggregate	700 kg/m^3	708 kg/m^3
10mm aggregate	350 kg/m^3	355 kg/m^3
Fine aggregate (sand)	700 kg/m^3	707 kg/m^3
Cement (CEM II/A-L)	400 kg/m^3	404 kg/m^3
Water	200 L/m3	202 L/m^3
Total	*2350 kg/m^3*	*2377 kg/m^3*

3.5.3. Standards and Tests

All tests in this thesis were conducted in compliance with the following standards, the test methods for these are given in detail in the said standards and are not reproduced here for brevity:

I.S. EN 206 Concrete-Specification, performance, production, and conformity

I.S. EN 12350-1, Testing fresh concrete, Part 1: Sampling

I.S. EN 12350-2, Testing fresh concrete, Part 2: Slump-test

I.S. EN 12350-4, Testing fresh concrete, Part 4: Degree of compactability

I.S. EN 12350-6, Testing fresh concrete, Part 6: Density

I.S. EN 12390-1, Testing hardened concrete, Part 1: Shape, dimensions, and other requirements for specimens and moulds

I.S. EN 12390-2, Testing hardened concrete, Part 2: Making and curing specimens for strength tests

I.S. EN 12390-3, Testing hardened concrete, Part 3: Compressive strength of test specimens

I.S. EN 12390-6, Testing hardened concrete, Part 6: Tensile splitting strength of test specimens

I.S. EN 12390-7, Testing hardened concrete, Part 7: Density of hardened concrete

BS EN 12390-13:2013, Determination of secant modulus of elasticity in compression

I.S. EN 12620:2002+A1:2008, Aggregates for concrete

I.S. EN 13263-1, Silica fume for concrete, Part 1: Definitions, requirements and conformity criteria

I.S. EN 15167-1, Ground granulated blast furnace slag for use in concrete, mortar and grout, Part 1: Definitions, specifications, and conformity criteria

I.S. EN 197-1, Cement

3.6. Precision

The flowing are major points derived from the above standards:

Weighing: The quantities of cement, each size of aggregate, and water for each batch shall be determined by weight to an accuracy of 0.1 percent of the total weight of the batch.

Preparation of Materials: All materials shall be brought to room temperature, preferably $23^{o} \pm 3$ C before conducting tests.

Cubes: 100*100*100 mm between moulded surfaces the tolerance on the designated size is 1.0 %

Cylinders: H: 300 D: 150 mm the tolerance on the designated diameter is 1.0 %

Moulds: Moulds are watertight and non-absorbent, coated with wax.

Compaction of the concrete: The concrete shall be compacted immediately after placing in the moulds in such a way as to produce full compaction of the concrete with neither excessive segregation nor laitance. Each layer shall be compacted by using the vibrating table, Apply the vibration for the minimum duration necessary to achieve full compaction of the concrete. The mould should preferably be attached to, or firmly held against the table. Avoid over-vibration, which may cause loss of entrained air.

Curing of test specimens: Test specimens are left in the mould for 1 day, at a temperature of 20° ± 5° C, protected against shock, vibration, and dehydration. After removal from the mould, the test specimens are cured in water at a temperature of 20° ± 2° C until tested.

Loading: a constant rate of loading at 0.6 ± 0.2 MPa/s (N/mm^2). loads applied to the specimen without shock and increase continuously at the selected constant rate ± 10 %, until no greater load can be sustained.

3.7. Results

Results, discussions, and conclusions are presented in individual chapters. In each chapter the following concrete properties are tested, illustrated, and discussed: slump, fresh density, compressive strength, and the elastic modulus. Properties were tested at various stages of the treatment methods.

Moreover, the final concrete mixes in each chapter are subjected to the particle packing theory to show its effect on the concrete properties. Therefore, it was necessary to demonstrate and explain the particle packing theory process first in the following chapter (Chapter 4) and then to continue as following:

- Chapter 4 Particle packing
- Chapter 5 Chipped rubber
- Chapter 6 Recycled concrete aggregate
- Chapter 7 GGBS
- Chapter 8 Combination
- Reference

Also, a preliminary test section was added below, which was considered as a starting point and a dry run for the thesis testing schedule.

3.8. **Preliminary test**

West (2015) described a project to present the ultimate available concrete sustainability. A concrete mix was designed with 85% GGBS, recycled aggregates, quarry dust, recycled tyres in the form of chipped rubber, harvested rainwater, and hemp as an anti-cracking agent. The four different designed mixes are illustrated in Table 3.6.

Table 3.6 Details of the concrete mix (West et al., 2015).

Mix	Cement	Sand	10mm Aggt.	20mm Aggt.	GGBS	Crumb Rubber	Recycled concrete	Processed grit	Quarry powder	H_2O
1	395	590	400	800	...	...	...	...	...	200
2	55	590	400	800	340	...	...	...	...	200
3	55	590	...	...	340	365	...	...	...	200
4	55	...	...	...	340	225	280	280	25	200

The development of the compressive strength, shown in Figure 3.6, was monitored over 56 days. In Mix 2, the high (85%) GGBS content caused a 30% drop in strength from 45 MPa to 32 MPa, suggesting that this is due to some of the GGBS not being hydrated without artificial stimulus and acting as an inert void filler. In Mix 3, when the natural aggregates were fully substituted with chipped rubber, the weight of aggregates after a volume mapping of limestone to rubber, reduced to 365 kg/m^3. The strength dropped further by up to 90% of the base strength to less than 5 MPa. This was predicted as the rubber is much more flexible than limestone and the cement paste had to take more of the load, which it was not designed to do. Also, the concrete was hard to compact and finish. Finally, in Mix 4 when other constituents (recycled aggregate, grit and quarry dust) where substituted, there was no remarkable effect on the strength compared to Mix 3, yet this concrete was more compactable and finishable (West et al., 2015). The RA contains weak adhered cement paste instead of virgin aggregate which explains the further drop in strength.

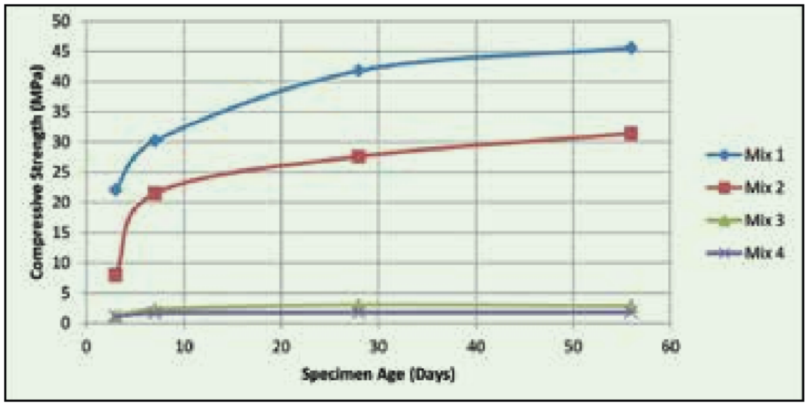


Figure 3.6 Strength development for concrete mixes (West et al., 2015).

It is quite evident that to create a highly sustainable concrete using mostly recycled materials poses very serious technical challenges regarding maintaining its mechanical properties and this is the subject of extensive future work reported on here. Correspondingly, it was concluded in Alawais and West (2016), titled “sustainable concrete with 95% recycled and natural components”, that concrete`s mechanical properties are affected significantly by using recycled materials, especially compressive strength and modulus of elasticity, yet it was surmised that the reduction in these properties when using these substances may be countered to some degree by:

- Soaking the rubber in NaOH
- Activating GGBS with alkaline activators
- Pre-treating the recycled aggregate
- Segregation of high strength RA for use
- Treating harvested rainwater prior to use

It is the objective of this research project to explore the range of options in an attempt to obviate the detrimental effects of the inclusion of these recycled materials on the strength and stiffness of concrete.

Chapter 4

Particle packing theory

4. Particle packing theory

Aggregate is the main portion in forming the concrete. Moreover, appropriate aggregate blend characteristics are important to guarantee good concrete mixes (Miao et al., 2018). In this chapter the research used particle packing charts and tables to design the concrete mix. This chapter illustrates on the method of particle packing, and how changing the amount of a one aggregate would affect the strength of concrete.

4.1. Objectives

The objective of this chapter is to investigate the effect of particle packing on the strength of concrete using Dewar (1983) method introduced in Chapter 2.

4.2. Methods

At the beginning an excel sheet was designed using the equations mentioned in the literature review in Section 2.7, equations from (2) to (12), to generate the particle packing table. Second, to examine the relation between several coarse and fine aggregate sizes in terms of void ratio. After that the compressive strength behaviour of concrete was tested for several points on the particle packing curve. Finally, this method is then used as a final approach in each of the following chapters to compensate for the strength loss as a result of using recycled and by-product constituents.

4.3. Void ratio diagram

For each two different aggregates in size, all the equations illustrated before in point 2.7. at the literature review are used in Table 4.1 to generate U_0'' and U_1'' for the points B, C, D and E which are used to generate the particle packing diagram Figure 4.1.

Shown in Table 4.1 the best particle packing between 20 mm coarse aggregates and normal sand, recycled sand, coarse sand, and fine sand are calculated to obtain a full understanding of the behaviour of particle parking's effect.

Table 4.1 Particle packing table for 20 mm / (normal sand, fine sand, coarse sand and recycled sand)

Aggregate	20 mm - Normal Sand			
Points	B	C	D	E
m spacing factor	0.30	0.75	3.00	7.50
r ratio between mean size	0.03	0.03	0.03	0.03
U0 voids ratio	0.89	0.89	0.89	0.89
U0"	1.28	1.42	1.74	2.04
K int	0.12	0.06	0.02	0.00
K p	0.60	0.65	0.80	0.90
Z	0.13	0.08	0.03	0.01
U 1	0.61	0.61	0.61	0.61
U 1"	1.51	0.96	0.70	0.63
Aggregate	20 mm - Fine Sand			
Points	B	C	D	E
m spacing factor	0.30	0.75	3.00	7.50
r ratio between mean size	0.02	0.02	0.02	0.02
U0 voids ratio	0.89	0.89	0.89	0.89
U0"	1.23	1.36	1.63	1.89
K int	0.12	0.06	0.02	0.00
K p	0.60	0.65	0.80	0.90
Z	0.13	0.07	0.02	0.01
U 1	0.54	0.54	0.54	0.54
U 1"	1.42	0.87	0.62	0.56
Aggregate	20 mm - coarse sand			
Points	B	C	D	E
m spacing factor	0.30	0.75	3.00	7.50
r ratio between mean size	0.05	0.05	0.05	0.05
U0 voids ratio	0.89	0.89	0.89	0.89
U0"	1.36	1.52	1.89	2.25
K int	0.12	0.06	0.02	0.00
K p	0.60	0.65	0.80	0.90
Z	0.14	0.09	0.04	0.02
U 1	0.64	0.64	0.64	0.64
U 1"	1.53	1.01	0.74	0.68
Aggregate	20 mm - recycled Sand			
Points	B	C	D	E
m spacing factor	0.30	0.75	3.00	7.50
r ratio between mean size	0.10	0.10	0.10	0.10
U0 voids ratio	0.89	0.89	0.89	0.89
U0"	1.48	1.69	2.16	2.61
K int	0.12	0.06	0.02	0.00
K p	0.60	0.65	0.80	0.90
Z	0.15	0.10	0.05	0.03
U 1	0.72	0.72	0.72	0.72
U 1"	1.65	1.14	0.86	0.78

From Table 4.1 the particle packing diagram in Figure 4.1 was generated by drawing straight lines as suggested by Dewar (2002), between points U_0 and U_1 with coordinates (0, U0) and (1, -1) and the points (0, 0) and (1, U1). From the same figure it is observed that point d and e are very close to each other and both have the lowest void content which is 0.260 m^3/m^3 that means that the solid content at that point is: $S_{n=} 1 - V_n$ (13)

Sn = 0.740 m^3/m^3

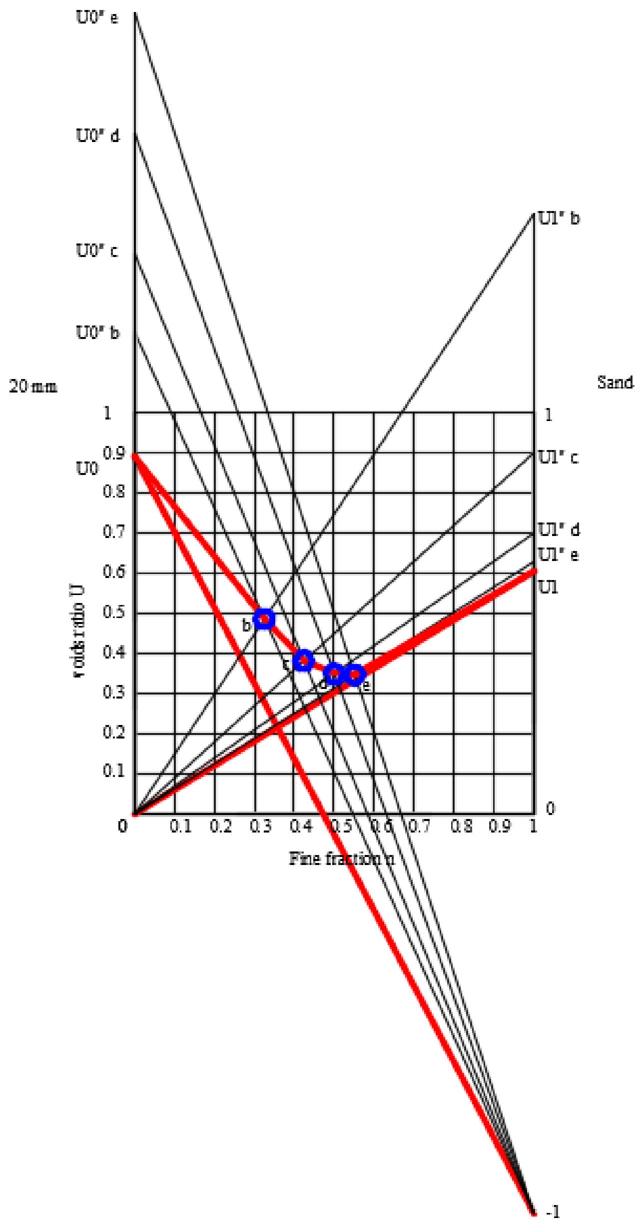


Figure 4.1 Particle packing diagram for 20 mm aggregates and normal sand

4.4. Coarse aggregate with different fine aggregates

As part of examining the effect of particle packing 20 mm aggregate was selected as a reference coarse aggregate to measure the effect of changing the sand type. In Figure 4.2 it is clearly shown that fine sand is the best in terms of less voids as a packing material that is the most compatible with the 20 mm aggregates.

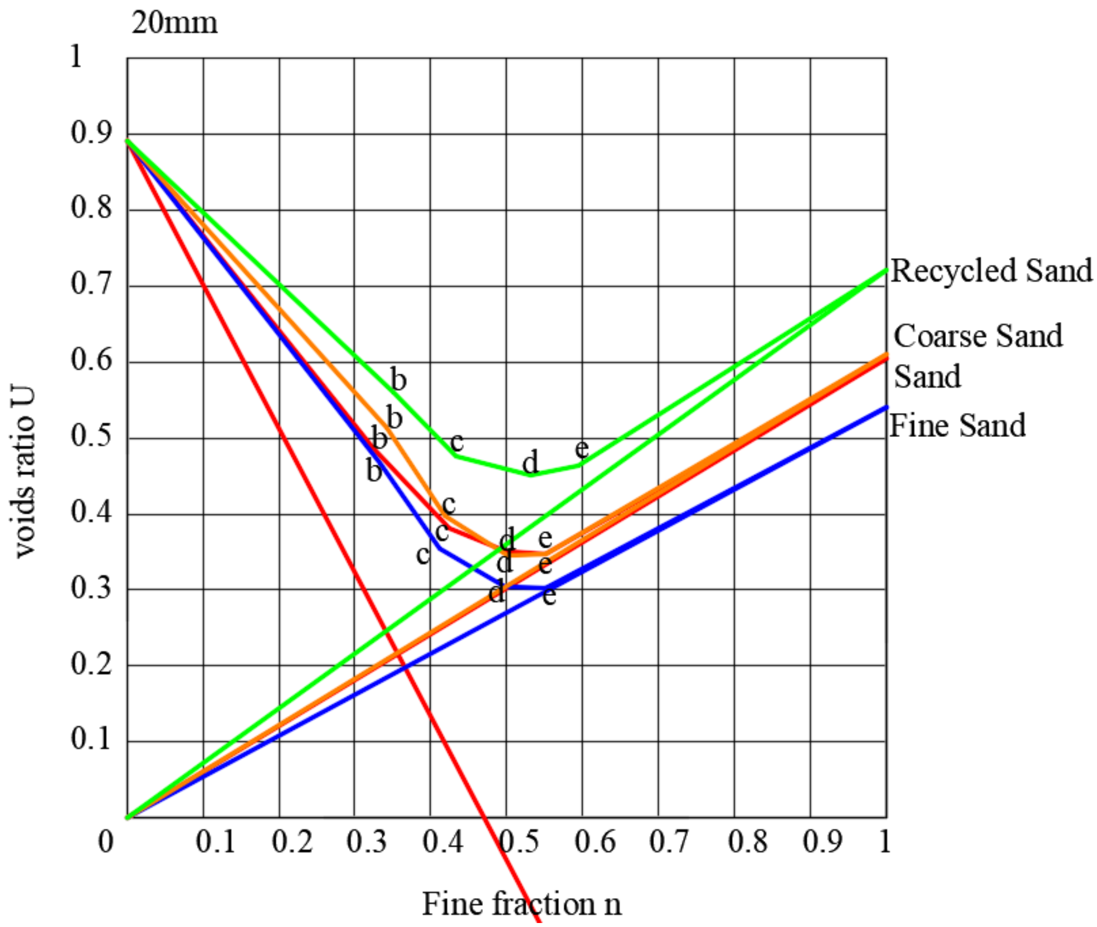


Figure 4.2 Particle packing diagram for different types of sand and 20 mm aggregates

Despite the recycled sand results due to the irregularity, Table 4.2 compares between the amount of each type of sand to use for the best packing.

Table 4.2 Amount of sand by percentage to 20 mm aggregates

point	Recycled sand (n)	Coarse sand (n)	Normal sand (n)	Fine sand (n)
b	39%	33%	34%	35%
c	42%	42%	43%	44%
d	50%	50%	52%	53%
e	55%	54%	57%	59%

4.5. Fine aggregate with different coarse aggregates

In this part the sand is maintained as a reference to examine the effect of changing the size of aggregate. Four different aggregate size illustrated in Figure 4.3 were selected 40mm, 20mm, 10mm and 6.3mm.

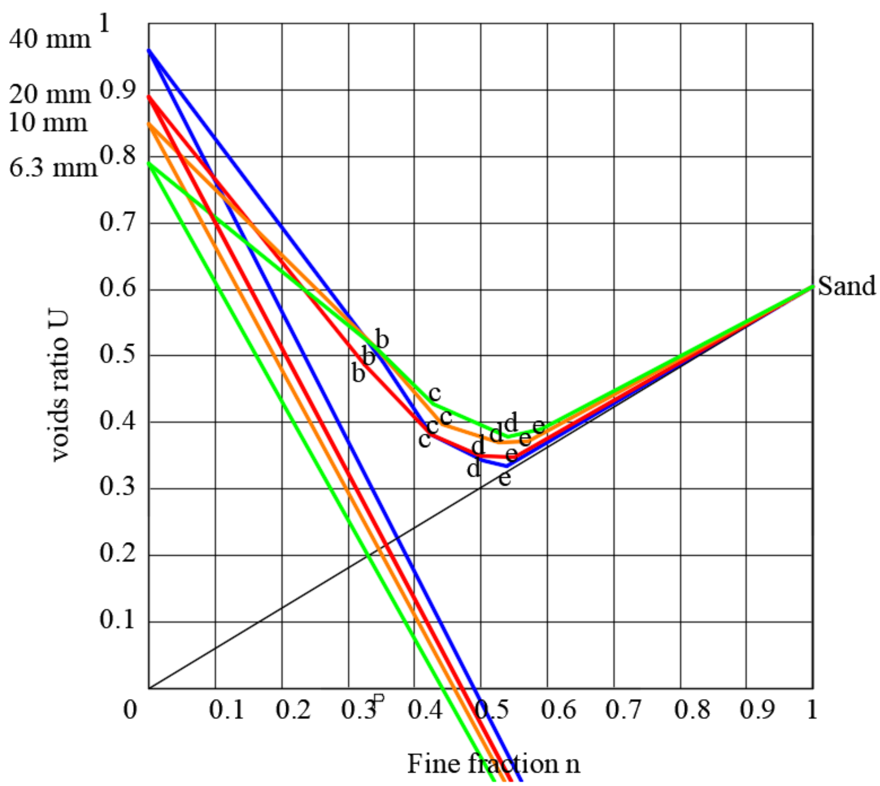


Figure 4.3 Particle packing diagram for different sizes of aggregates

It is clear at the left-hand side of the figure above that 40 mm has a greater void ratio than 6.3 mm. However, at point e, which is the lowest void ratio point for all types of aggregates. it is observed that 40 mm has much less particle packing voids than 6.3mm at the same point. In Table 4.3 the same point e is illustrated in more detail for all four types of aggregate. It is notable that in 6.3 mm 40% of the coarse aggregate is recommended with an approximate void ratio of 40% of the total mass. On the other hand, for the 40 mm aggregate with the same sand it is highlighted that 45% is the best amount to get the least amount of voids ratio which is around 35% of the total mass.

Table 4.3 Amount of aggregate by percentage using normal sand

point	6.3 mm	10 mm	20 mm	40 mm
b	65%	65%	66%	65%
c	56%	56%	57%	57%
d	46%	47%	49%	49%
e	40%	42%	44%	45%

The void ratio is the amount of void in relation to the amount of solid. In order to get the exact void content at a certain point (Vn) the void content equation 12 from above was applied. shown in Table 4.4 the exact void content for point e in all four types of aggregate. Illustrated in the table is a decreasing trend of void content with the increase of aggregate size.

Table 4.4 Void content using normal sand

	6.3 mm	10 mm	20 mm	40 mm
Void content (Vn) in m^3/m^3	0.283	0.273	0.260	0.256

4.6. Compressive strength

To test the effect of particle packing on compressive strength, water-to-cement ratio (W/C) of 0.5 is fixed in all mixes conducted in this research. At first a particle packing diagram for 20 mm, 10 mm generated that is to know the relation between 20mm and 10mm in terms of packing shown in Figure 4.4.

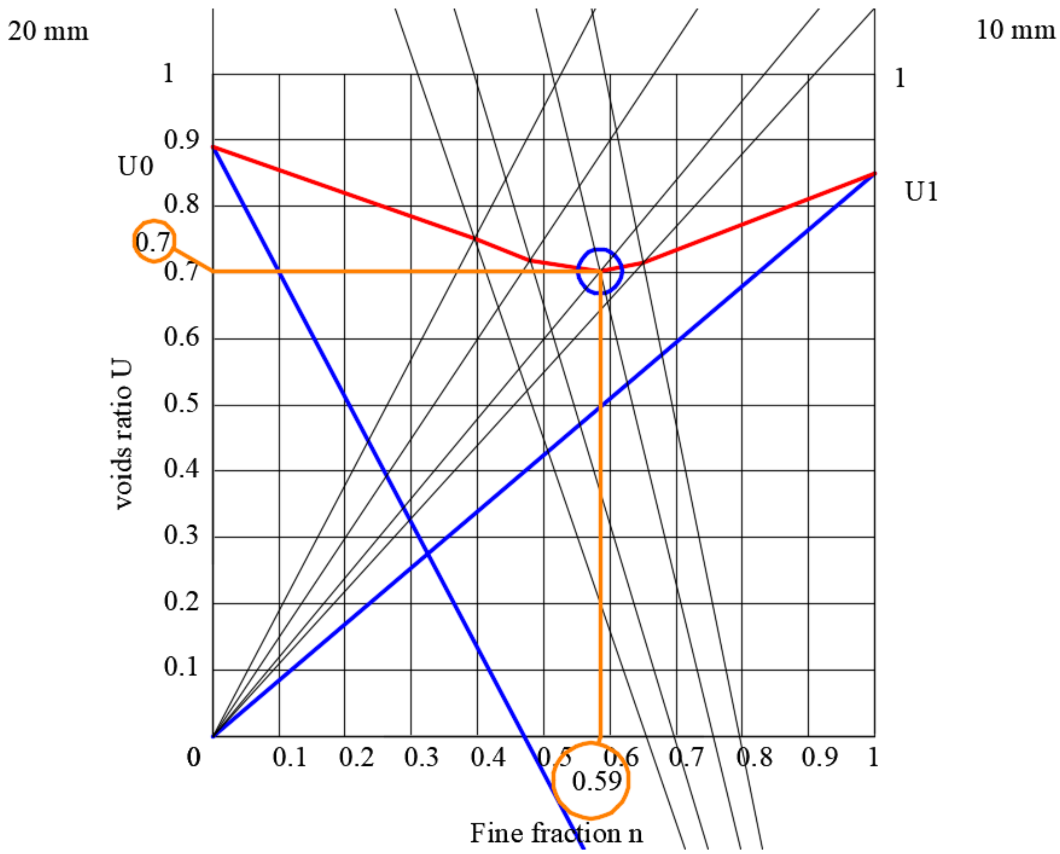


Figure 4.4 Particle packing diagram for 20 mm and 10 mm

It is suggested by the diagram that point 0.7 is the lowest void ratio point for 20 mm and 10 mm aggregates mixed together with an amount of 0.59% of 10 mm and 0.41% of 20 mm. Next, another particle packing diagram was generated that has 20 mm and 10 mm aggregates mixed as coarse aggregates and sand as fine (Figure 4.5).

Following that, five random points were well-spared among the void ratio curve of the particle packing diagram. Point (C) represents the best particle packing point in the diagram. Furthermore, Table 4.5 shows the constituents of all mixes based on the particle packing diagram.

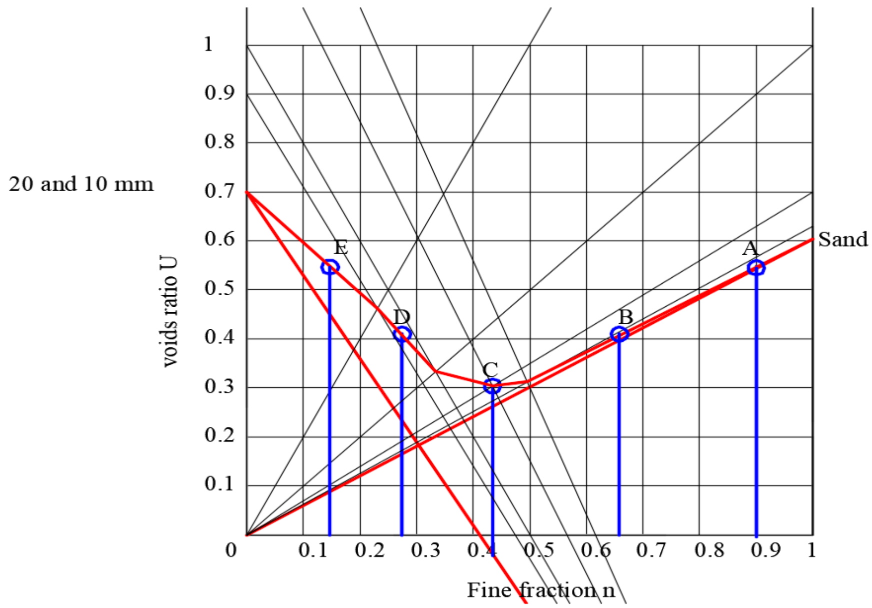


Figure 4.5 Particle packing diagram

Table 4.5 Concrete mixes design

Mix	Coarse aggregates 20 and 10 mm	Sand	Cement	Water
A	175 kg/m^3	1575 kg/m^3	400 kg/m^3	200 L/m^3
B	595 kg/m^3	1155 kg/m^3	400 kg/m^3	200 L/m^3
C Best particle packing	980 kg/m^3	770 kg/m^3	400 kg/m^3	200 L/m^3
D	1260 kg/m^3	490 kg/m^3	400 kg/m^3	200 L/m^3
E	1505 kg/m^3	245 kg/m^3	400 kg/m^3	200 L/m^3

The compressive strength results are shown in Figure 4.6 and Table 4.6 It is clearly observed that particle packing has a significant amount of effect on the compressive strength of the concrete. At point (C) the compressive strength is at its peak.

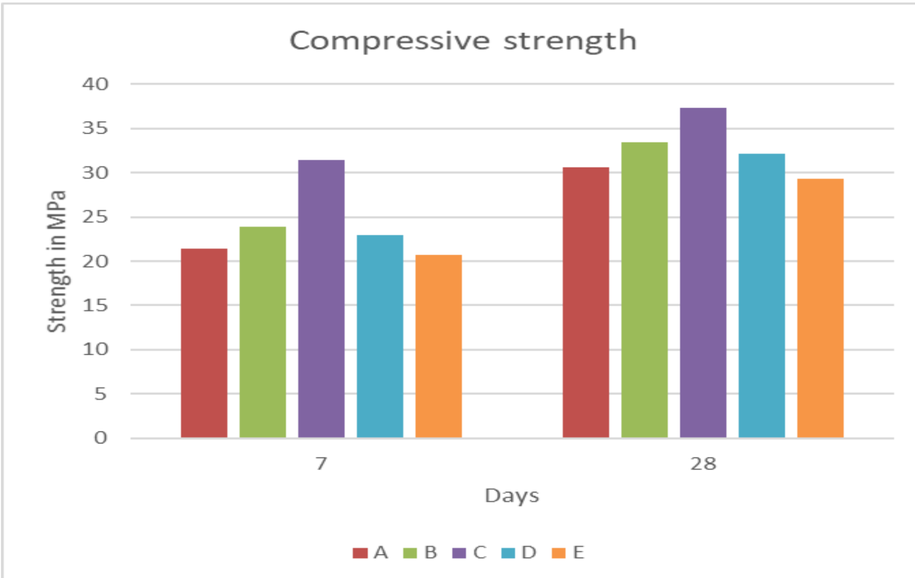


Figure 4.6 Compressive strength for point A,B,C,D and E at 7 and 28 days

Table 4.6 Compressive strength and average compressive strength in MPa for point A,B,C,D and E at 7 and 28 days

Day	Compressive strength in MPa									
	A	A Average	B	B Average	C	C Average	D	D Average	E	E Average
7	21.8	21.38	24	23.88	30.1	31.48	23.4	22.94	21.2	20.68
	21.4		23.4		32.4		22.6		20.9	
	20.7		23.8		31		22.9		20.5	
	21.7		24.3		31.4		23.3		21	
	21.3		23.9		32.5		22.5		19.8	
28	30.2	30.58	33.4	33.4	38.5	37.52	32.5	32.16	29.2	29.26
	29.8		34		37.4		31.9		29.5	
	31.2		33.5		37.8		31.6		28.7	
	31		33.1		36.9		32		30	
	30.7		33		37		32.8		28.9	

In Figure 4.7 the compressive strengths for 7 and 28 days are plotted on the particle packing diagram to show an integrated relationship between them. It is observable that the better the packing of the aggregates the greater the strength of the concrete which now justifies this approach.

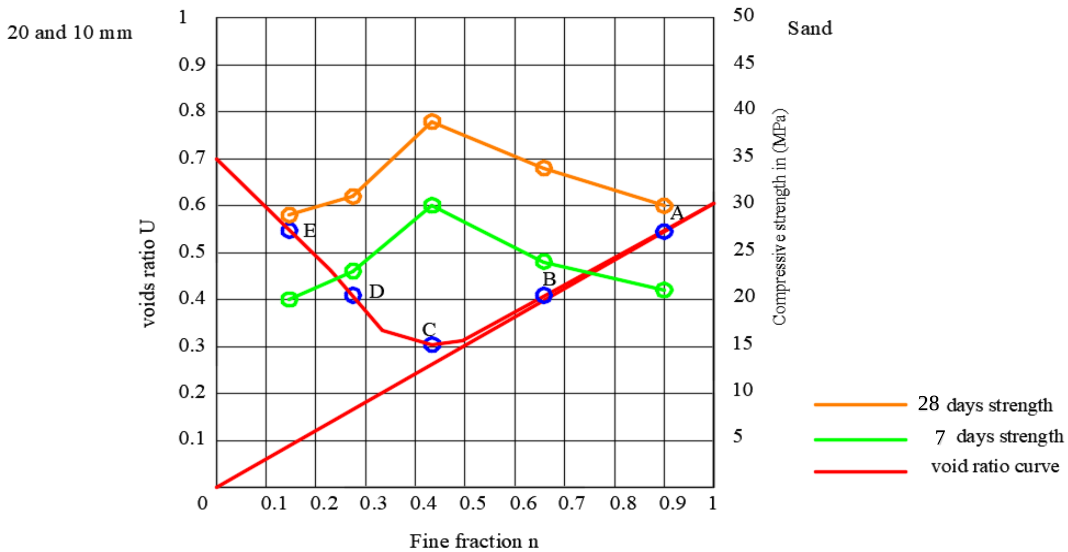


Figure 4.7 Compressive strength X particle packing diagram

Partial packed Mix C is then compared with the reference mix in 3.5.2 in terms of the compressive strength illustrated in Table 4.7 and Figure 4.8.

Table 4.7 Mix C (particle packed) and reference mix compressive strength

Day	Compressive strength in MPa			
	Reference mix	Average	Particle parked	Average
7	24.5	24	30.1	31.48
	21.5		32.4	
	23.5		31	
	25		31.4	
	25.5		32.5	
28	35.5	34.3	38.5	37.52
	34		37.4	
	35		37.8	
	33		36.9	
	34		37	
56	39	37.8	42.7	43.18
	38		43.8	
	37		43.2	
	36.5		44	
	38.5		42.2	

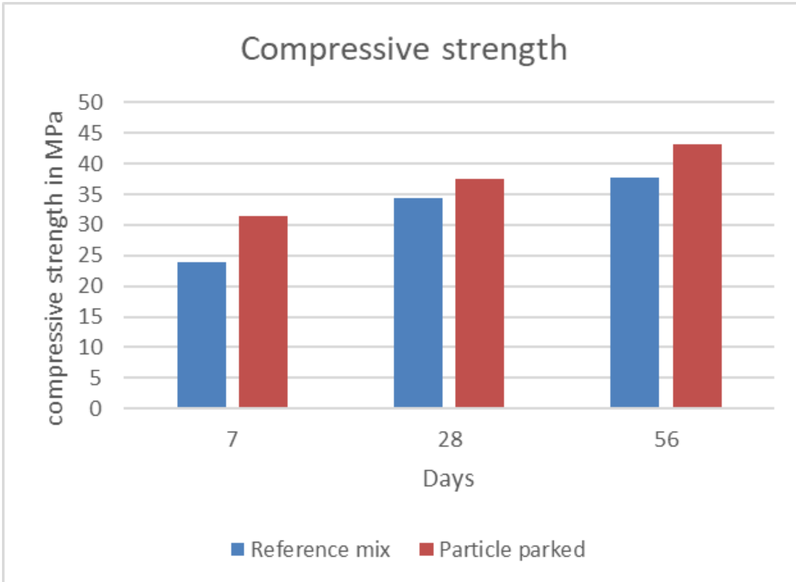


Figure 4.8 Mix C (particle packed) and reference mix compressive strength

Particle packed concrete mixes are about 9% greater in compressive strength than unpacked concrete at 28 days and has 14% more compressive strength after 56 days than unpacked concrete. Therefore, this study will use the particle packing method as a final approach to enhance recycled concrete strength in the following chapters.

4.7. Conclusions

This chapter has investigated the particle packing relationship between different sizes of coarse aggregates and fine aggregates and the effect of particle packing on the compressive strength of the concrete. The following conclusions are drawn from this chapter:

- The void ratio diagram is a significant tool to display the relationship between two different aggregates sizes. Also, it is helpful to pinpoint the best packing ratio of these two aggregates.
- The greater the mean size difference between adjacent materials the smaller the void ratio that is detected.

- Particle packing enhanced the compressive strength of concrete; thus, the following chapters will use the particle packing method as a final approach to compensate for the loss of concrete strength when using recycled and by-product materials.

Chapter 5

Chipped rubber

5. Chipped rubber

This chapter will illustrate the usage of chipped rubber as a replacement of normal aggregate in a concrete mix. Moreover, it will investigate the addition of the 6.3 mm waste aggregates to chipped rubber to enhance its strength. The chipped rubber used in this research was obtained from a recycling car tyres company, NR Rubber Products Ireland (Figure 5.1).

Figure 5.1 Chipped rubber aggregate compared to a mixed limestone aggregate

Waste used car tyres are shredded down to size 8-19 mm and all steel wires are removed from them. A particle size distribution analysis was conducted to compare with normal limestone aggregates (Figure 5.2), then chipped rubber was sieved and used at a 100% replacement rate for the traditional 20mm and 10mm aggregates.

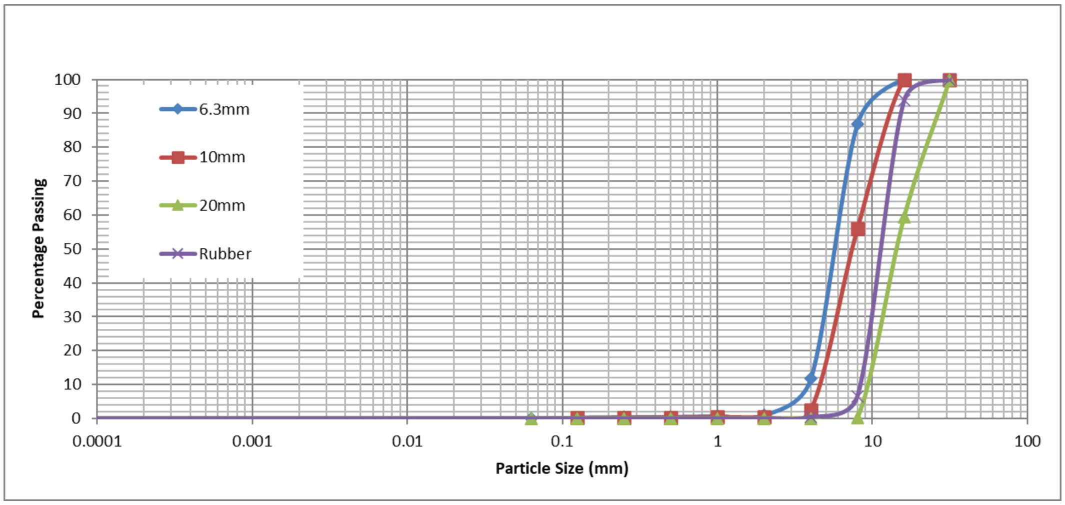


Figure 5.2 Particle size distribution of normal 20, 10 and 6.3mm limestone and the chipped rubber

5.1. Objective

The objective of this chapter was to investigate the effects of replacing 100% of the coarse aggregate with chipped rubber and, specifically, to establish the advantages of pre-treating by:

- Ultra-violet treatment
- Sulphuric acid treatment

A second objective is to consider enhancing the strength further by adding 6 mm by-product aggregate. Furthermore, it is an objective to use particle packing as a final approach to get the best packing out of 6.3 mm waste aggregates and chipped rubber combined together, to compensate for the strength loss.

5.2. Chipped rubber pre-treatment

5.2.1. Ultraviolet light pre-treatment

Chipped rubber was sieved like a normal aggregate on 20 mm and 10 mm sieves, to create the same aggregate size and volume as the normal aggregates used in the reference mix. After sieving, the chipped rubber was spread out thinly on the floor and exposed to the ultraviolet light enclosed in a box designed for this purpose (Figure 5.3).

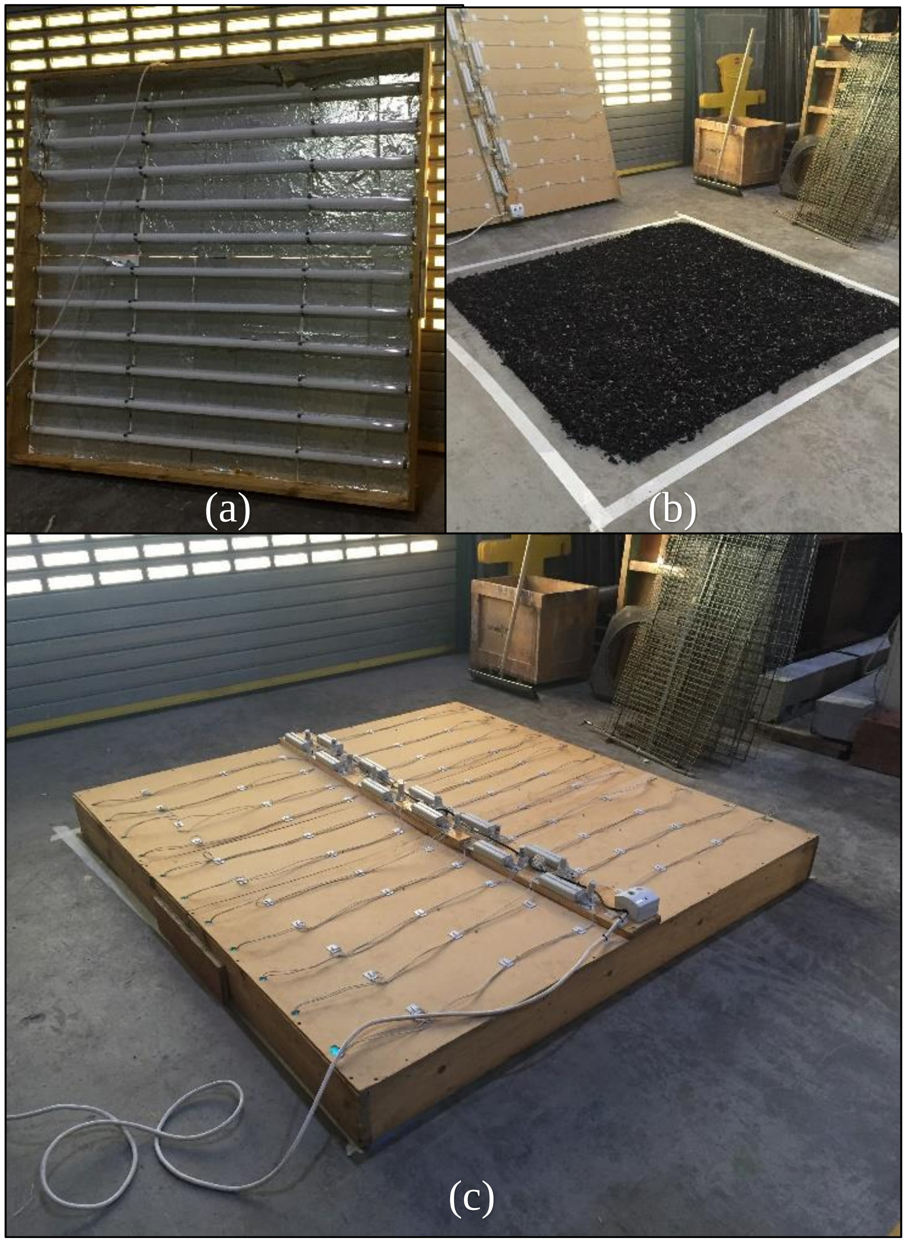


Figure 5.3 (a) ultraviolet light tubes. (b) chipped rubber aggregates (c) ultraviolet light box on the rubber aggregates

During each day, over 8 hours of daily exposure, the covered light box was lifted, the chipped rubber was mixed, and the light box was brought back on top of the rubber. Although the temperature of the rubber increased somewhat under exposure, it was not high enough to cause the rubber to melt. This procedure was repeated for 15 days, amounting to a total exposure time of 120 hours. If successful, this technique could be automated in a tyre recycling factory setting.

5.2.2. Sulphuric acid treatment

Chipped rubber was soaked for 1 hour in a 95% concentrated sulphuric acid solution, during which the chipped rubber was agitated. Next, the chipped rubber was allowed to dry in plastic containers for 24 hours. Then the chipped rubber was rinsed with water until there was no odour trace of the sulphuric acid in the washing water. Water pH was not tested to clarify the trace of acid but is recommended in a factory setting should the technique be successful. Chipped rubber was then left to dry for one week before being used in the rubberized concrete mixes (Figure 5.4).

Figure 5.4 chipped rubber left to dry in plastic container

5.3. Chipped rubber aggregate stiffness

A sample of 3 random batches of un-treated chipped rubber was prepared to be tested for their California bearing ratio (CBR) value (Figure 5.5).

Figure 5.5 California bearing ratio (CBR) testing apparatus

Another 3 random sample of UV treated rubber were also batched and tested. The plunger was set to move 1 mm every minute for 20 mm and a plot of force against displacement was produced. Figure 5.6 represents all 6 samples, from which it is clearly the case that the UV treated samples are stiffer than un-treated rubber samples, amounting to an increase of about 30% in the average CBR value at 15mm.

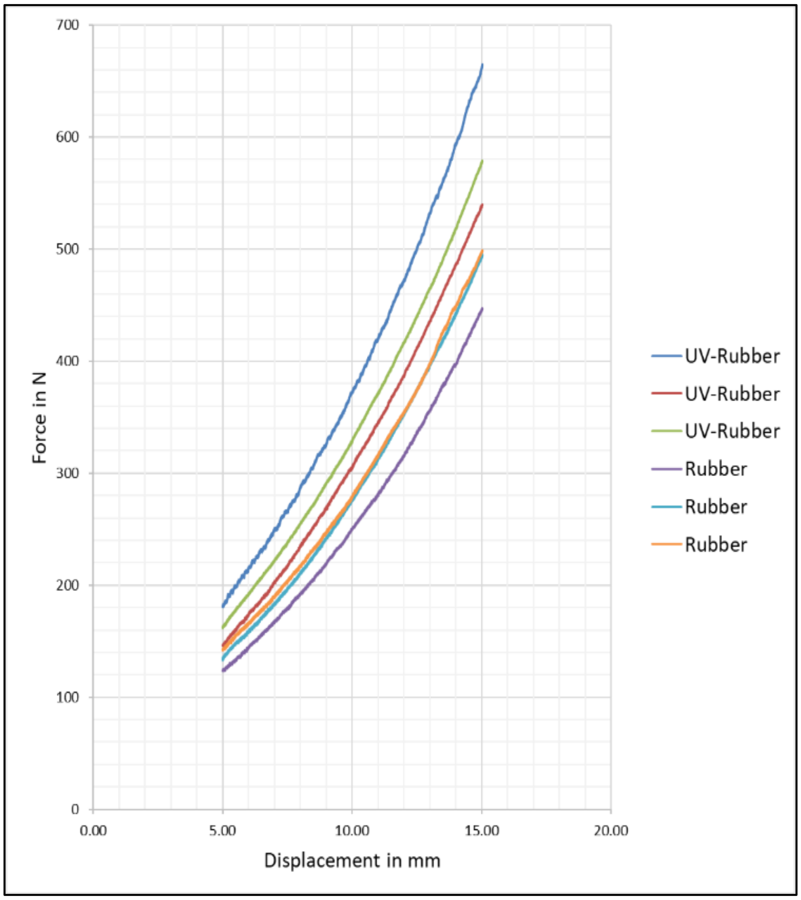


Figure 5.6 CBR results on untreated chipped rubber and treated with UV light

This is most likely because of the limitations of the UV light treatment, as it was only affecting the surface and not penetrating to the core of the rubber particles. Cement paste will still be expected to provide significant load resistance in a concrete compression test as the chipped rubber, even when UV treated, is so flexible. This partially explains the significant drop in strength when rubber is added.

On the other hand, Figure 5.7 demonstrates the CBR results for three random H_2SO_4 treated chipped rubber samples. The plunger was set to move 1 mm every minute for 20 mm and a plot of force against displacement was produced.

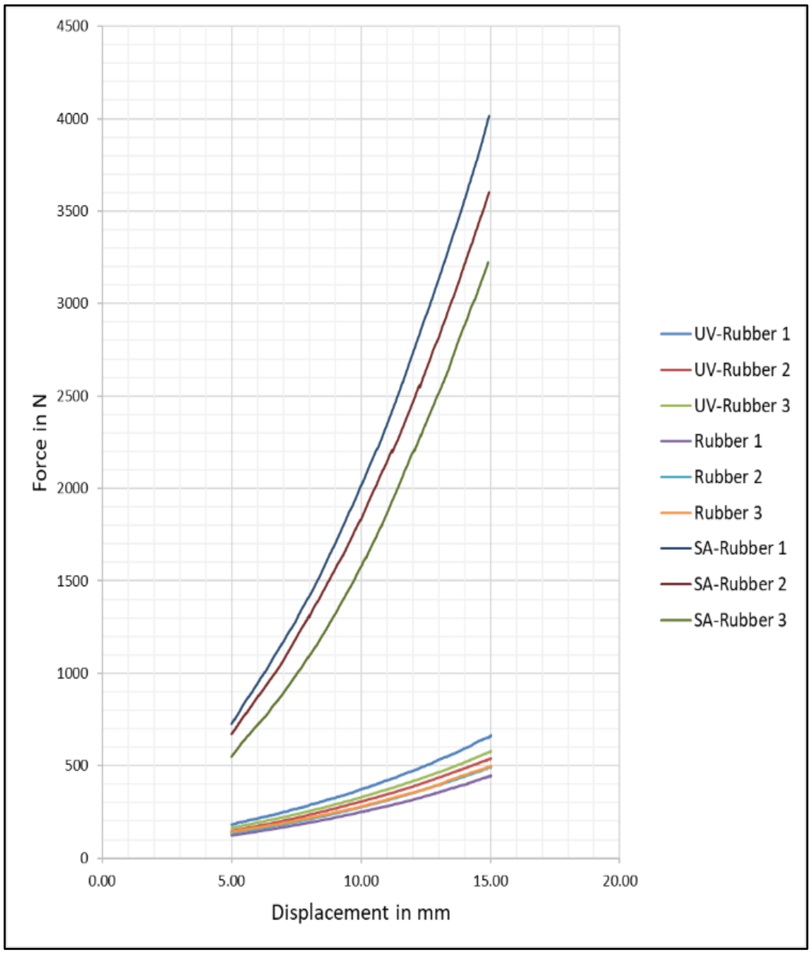


Figure 5.7 CBR results on treated and untreated chipped rubber with sulfuric acid

It is clear that sulfuric acid treatment has a more than 600% increase in chipped rubber stiffness than UV-light treatment.

5.4. Specimens casting and curing

The concrete mixing matrix is illustrated in Figure 5.8. For each pour, a total of 15 (300 mm x 150 mm) cylinders and 4 (100 mm x 100 mm) cubes were cast. The cubes were included to ensure independently that the two batches match in terms of their 28 days compressive strength requirement. Five cylinders were tested respectively at 7, 28 and 56 days for strength and elastic modulus.

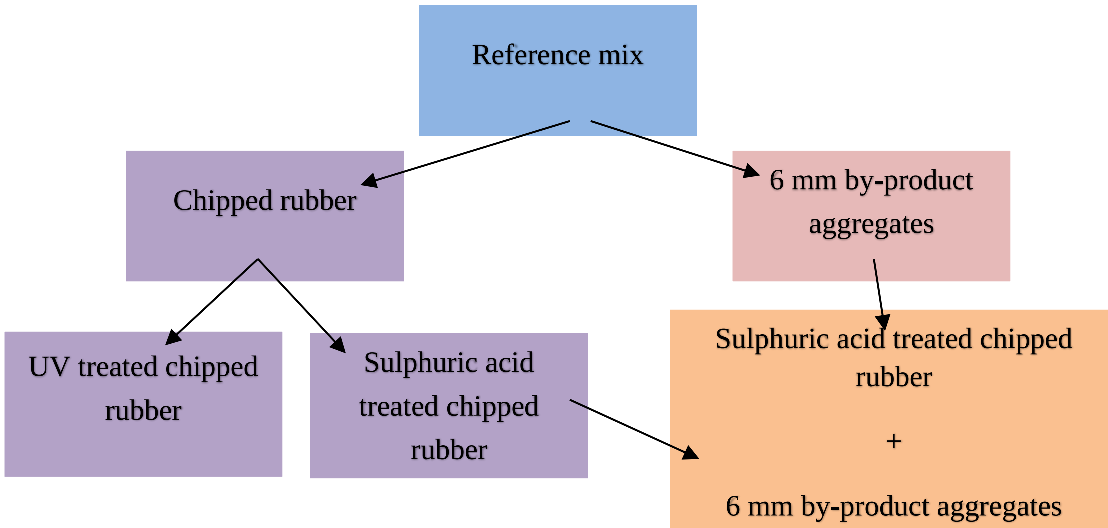


Figure 5.8 Mix matrix schematic

5.5. Chipped rubber mix

Chipped rubber was substituted into the baseline normal aggregate mix by equal volume not by weight due to the difference in density between limestone and rubber. Table 5.1 shows the quantities of each mix with their mix identifier labels.

Table 5.1 Chipped rubber concrete mix quantities, R: chipped rubber

Mix	Note	Coarse aggregates			Sand	Cement	Water	Fresh Average density
		R/20 mm	R/10 mm	6.3 mm				
RC	Reference concrete mix	708 kg/m³	355 kg/m³	-	707 kg/m³	404 kg/m³	202 L/m³	2377 kg/m³
CRC	Chipped rubber aggregates	240 kg/m³	120 kg/m³	-	675 kg/m³	384 kg/m³	192 L/m³	1612 kg/m³
UV-CRC	UV treated chipped rubber aggregates	251 kg/m³	126 kg/m³	-	705 kg/m³	404 kg/m³	202 L/m³	1687 kg/m³
SA-CRC	Sulphuric acid treated chipped rubber aggregates	350 kg/m³	175 kg/m³	-	700 kg/m³	400 kg/m³	200 L/m³	1822 kg/m³
SA-CRC6A	Sulphuric acid treated chipped rubber aggregates + 6 mm by-product aggregate	200 kg/m³	100 kg/m³	350 kg/m³	700 kg/m³	400 kg/m³	200 L/m³	1942 kg/m³
SA-CRC6A-PP	Sulphuric acid treated chipped rubber aggregates + 6 mm by-product aggregate + particle packed	151 kg/m³	101 kg/m³	504 kg/m³	705 kg/m³	402 kg/m³	201 L/m³	2065 kg/m³

5.6. Fresh concrete properties

Density and Slump tests were conducted for all mixes in accordance with IS EN 12350 parts 2 and 4 as mentioned in Chapter 3. Table 5.2 displays the change in density and slump corresponding to the chipped rubber treatment method. This is compatible with Thomas and Gupta (2015) results as they also demonstrated a decrease in the concrete's density when chipped rubber is used to substitute normal aggregates in their work.

Table 5.2 Density and slump for all concrete mixes

Mix	Density		Slump	
	Batch 1	Batch 2	Batch 1	Batch 2
RC	2380 kg/m^3	2375 kg/m^3	145 mm	150 mm
CRC	1585 kg/m^3	1640 kg/m^3	60 mm	65 mm
UV-CRC	1695 kg/m^3	1680 kg/m^3	160 mm	155 mm
SA-CRC	1800 kg/m^3	1845 kg/m^3	190 mm	195 mm
SA-CRC6A	1960 kg/m^3	1925 kg/m^3	70 mm	75 mm
SA-CRC6A-PP	2052 kg/m^3	2078 kg/m^3	65 mm	70 mm

For the first chipped rubber concrete mix (CRC), chipped rubber was not treated thus it still had its original tyre-designed characteristics. Furthermore, CRC mixes are lighter than normal concrete, so the hydraulic stress at the base of the slump cone was lower (due to lower self-weight where chipped rubber density was about 480 kg/m^3 compared to the limestone of 2650kg/m^3) and so the rheological yield value was not exceeded and that is principally why the slump was lower in comparison. Even though it changed from an S3 to an S2 class, where the slump test is still an appropriate consistency test to use. The UV-treated chipped rubber mix has a greater slump, probably due to the effect of the surface treatment. Even though the surfaces had cracks (shown with a red arrow), as shown in Figure 5.9, overall it had become much smoother.

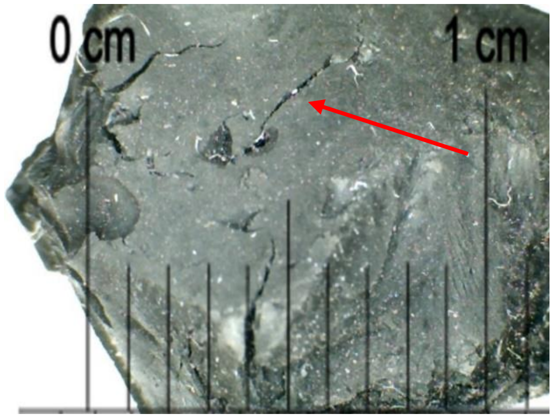


Figure 5.9 UV-treated chipped rubber surface cracks

Finally, the sulphuric acid treated chipped rubber mix (SA-CRC) showed a significant level of workability and a notable rise in density compared to the un-treated mix. With this level of treatment, chipped rubber had lost most of its angular edges and its surface had become smooth (Figure 5.10). In the SA-CRC6A case, the mix density was higher than in the SA-CRC case due to partial replacement of the chipped rubber with the smaller 6.3 mm waste limestone aggregates and higher density (2650kg/m^3) which also had an effect on the workability due to the increase of surface area and additional weight.

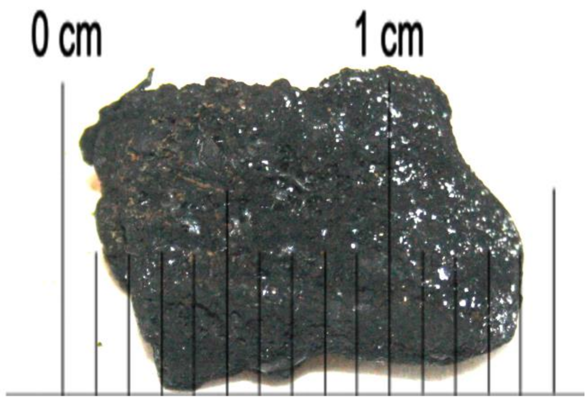


Figure 5.10 sulphuric acid treated chipped rubber surface

It is expected that the CRC mix will have a lower density as rubber is much less dense than limestone. However, after treating the rubber with the UV light, it was 7% denser, which could be due to cracks appearing on the surface of the chipped rubber which allow for better packing through crack filling with sand and cement paste.

Chipped rubber mixes approximately are 14% denser when the chipped rubber was treated with the sulfuric acid due to better packing caused by that change in surface and shape of the chipped rubber. Moreover, the density further improved by 24% when the chipped rubber was partially replaced with 6.3 mm limestone by-product aggregate, and by about 30% when chipped rubber and 6.3 mm aggregates were particle packed.

5.7. Compressive strength

The reference mix had a 34.4 MPa cylinder compressive strength after 28 days. The un-treated rubber reference mix had a very low strength as expected, with an average compressive strength of 2.8 MPa after 28 days (Table 5.3). This result agrees with Son et al. (2011) where they pointed out a measurable loss of strength due to partial chipped rubber usage in concrete. This was due partly to the poor adhesion between the chipped rubber aggregates and the cement paste but was mostly because of the measured low elastic modulus of the chipped rubber aggregates. When load is applied, the rubber aggregate deforms considerably (due to its very low E value) and transfers its load to the cement matrix which now carries most of the load, hence the dramatic decrease in measured compressive strength.

Table 5.3 Cylinder compressive strength of mixes CRC, UV-CRC, SA-CRC, SA-CRC6A and SA-CRC6APP

Day	Compressive strength in MPa											
	Reference mix	Average	CRC	Average	UV-CRC	Average	SA-CRC	Average	SA-CRC6A	Average	SA-CRC6APP	Average
7	24.5	24	2.7	2.8	3	3.1	4.9	5.2	10.1	9.8	16	17
	21.5		3		3.2		5.1		9.6		16.5	
	23.5		2.7		3.1		5.2		10.2		18	
	25		2.8		3.2		5.2		9.5		17	
	25.5		2.6		2.9		5.4		9.5		17.5	
28	35.5	34.3	3	3.0	3.2	3.3	7	7.4	13.5	13.0	22.5	22.8
	34		2.9		3.4		7		13.7		22	
	35		3		3.2		7.5		12.5		23.5	
	33		3		3.3		8		13		22.5	
	34		2.9		3.4		7.5		12.2		23.5	
56	39	37.8	3	3.1	3.2	3.3	8	8.7	15	14.6	25	24.9
	38		3		3.4		9.2		14.5		24.5	
	37		2.9		3.4		8.5		14		25.5	
	36.5		3.3		3.3		8.7		15.5		25	
	38.5		3.1		3.2		9		14		24.5	

The original reference concrete mix (RC) is illustrated in this section for reference purposes only and the CRC mix is used for all comparisons as the baseline for the subsequent comparisons with treated CRC mixes.

When the chipped rubber aggregates were treated with UV light, as stated previously, it mainly affected the surface of the rubber. That created a better bond with the cement paste, yet the bond alone was not enough because, as Figure 5.11 shows, there was only about a 10% improvement in the concrete's strength.

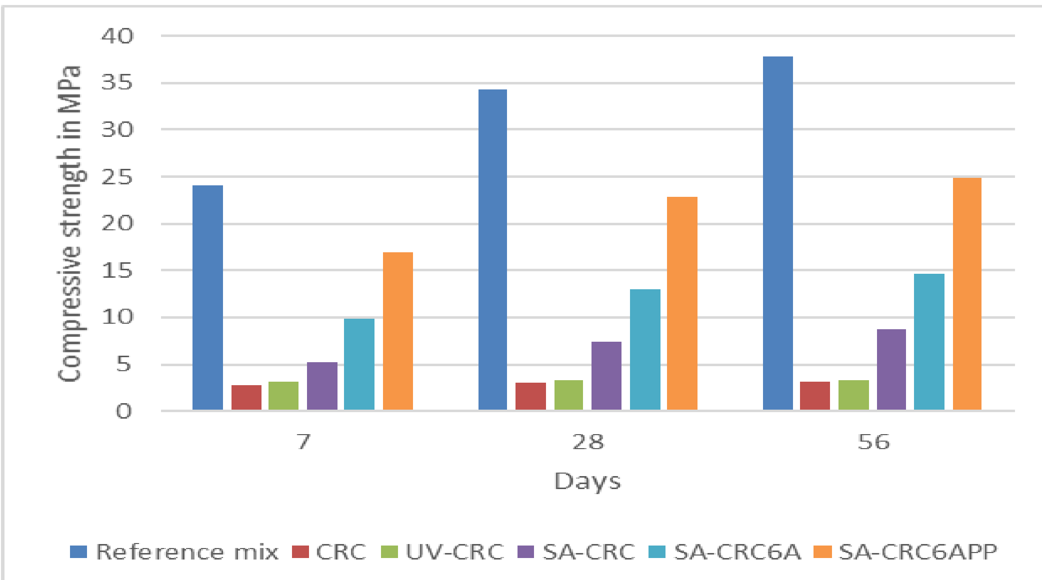


Figure 5.11 Compressive strength for: CRC, UV-CRC, SA-CRC, SA-CRC6A and SA-CRC6APP

Thus, the UV treatment of chipped rubber contributed little to increasing the strength, with an average compressive strength of 3.3 MPa after 28 days, which was within experimental error of the previous result. Alternatively, the sulphuric acid treated chipped rubber aggregate showed a much larger improvement in the compressive strength, about a 143% increase in 28 days average compressive strength of 7.5 MPa and 9.0 MPa after 56 days. This was due to the higher level of stiffness of the sulphuric acid treated rubber aggregates and better cohesion between cement paste and rubber aggregates. In the SA-CRC6A mix, the compressive strength increased by 333% comparing to the original CRC mix, due to the addition of the 6.3 mm limestone by-product aggregates. Finally, with the particle packed mix SA-CRC6APP the compressive strength increased about 660% and that illustrated that the percentage of compensated strength when comparing to normal aggregate concrete (RC) was about 65%.

This means that treating chipped rubber with sulphuric acid and then particle packing it with 6.3 mm waste aggregates shows an improvement of about 650 % in terms of compressive strength and could be suggested to be used for structural purposes.

5.8. Elastic modulus

The reference mix's elastic modulus after 28 days was about 30 GPa. The elastic modulus results for the treated mixes are represented in Table 5.4. Two cylinders were tests for modulus of elasticity in accordance with the standard mentioned in Chapter 3.

Table 5.4 Modulus of elasticity for chipped rubber concrete in GPa

Mix	7 days		28 days		56 days	
RC	23.1	24.3	29.8	28.0	29.3	30.4
CRC	1.2	1.3	1.8	1.9	2.0	2.0
UV-CRC	1.9	1.9	3.0	3.0	3.3	3.2
SA-CRC	5.1	5.0	7.5	7.6	8.2	8.0
SA-CRC6A	14.2	15.0	17.0	17.0	18.0	18
SA-CRC6APP	16.5	17.0	19.0	18.4	19.5	19.6

The untreated rubber mix E value average was about 1.8 GPa after 28 days, which is expected for a mix using 100% untreated chipped rubber with an average E value of 0.3 GPa. In the UV light treated mix, the E value increased by about 60% and that is reflected in the overall elastic modulus of the concrete. On the other hand, sulfuric acid treatment had a notable 322% increase in the chipped rubber elastic modulus, at 7.5 GPa after 28 days. In the SA-CRC4A mix after partially replacing the chipped rubber with the 6.3 mm limestone the elastic modulus improved to 17.0 GPa after 28 days. Finally, in the SA-CRC6APP the elastic modulus increased by 980% to reach 19.0 GPa at 28 days. This implies that treating chipped rubber with sulphuric acid and then particle packing it with 6.3 mm waste aggregates is effective and had a significant improvement on the concrete's elastic modulus.

5.9. Failure type

Cylinder failure was first observed by bulging near the top and spreading downwards, consistent with the observations of Miller and Tehrani (2017). Furthermore, the rubber particles bound the concrete together post peak (Figure 5.12). This energy absorption through a "soft" response may be useful in impact loading circumstances. This could be very suitable to be used in road barriers and pedestrian pavements as parts of concrete will not shatter because of impact.

Figure 5.12 Rubber aggregate concrete cylinder's failure type

5.10. Conclusions

This chapter determined the treatment method's effect on chipped rubber concrete mechanical properties, from which the following conclusions may be drawn:

- When replacing normal aggregates with a 100% chipped rubber aggregates, a given weight of the aggregates will produce a greater volume, so batching of aggregate should be done by volume.

- The untreated rubber concrete mix is less workable due to the characteristics of chipped rubber such as lower surface bond and water repellence, but also primarily because it is lighter.
- Ultraviolet treatment mainly affects the surface of the rubber, causing a smoother surface but with small cracks on the surface. The cracks improve the bond with cement paste and the smoother surface increases workability.
- Sulphuric acid treatment significantly enhances the chipped rubber stiffness, and it contributes in eliminating the angularity in the chipped rubber aggregates, making their surfaces smoother than the ones treated with ultraviolet light.
- Both ultraviolet and H_2SO_4 treatments positively impacted the behaviour of chipped rubber aggregates in a concrete matrix. And both treatment methods helped in regaining concrete workability.
- Ultraviolet light chipped rubber treatment increased the strength of concrete by 10%. However, sulfuric acid treatment had a significant effect in increasing the strength of concrete by 143%, principally due to stiffening of the aggregate.
- Adding 6 mm limestone as a partial replacement of the chipped rubber to the sulfuric acid treated chipped rubber mix increased the strength by a further 75% and decreased the workability due to the larger surface area of the 6 mm aggregates, despite their higher density.
- Particle packing chipped rubber with the 6 mm by-product aggregate increases the compressive strength by about 650 % and the elastic modulus by 980% above the respective baselines.
- Failure type characteristics suggest that chipped rubber concrete is suitable to be used in road barriers and pedestrian pavements as the concrete will not shatter due to impact.

Chapter 6

Recycled concrete aggregates

6. Recycled concrete aggregates

6.1. Objective

The objective of this chapter was to examine the effect of a 100% replacement of normal aggregates with recycled concrete aggregate in the concrete mix on the compressive strength and modulus of elasticity; this test would clarify how the strength of the recycled aggregate can influence the strength grade of concrete. Also, the segregation of waste concrete aggregates based on strength before crushing is expected to contribute positively to achieving the desired properties. This research will also propose the pre-treatment of the RCA, by coating with silica fume (SF), to enhance the strength and reduce the surface porosity of the RCA. Also, this chapter will investigate the effect of drying the RCA before the pre-treatment with micro silica fume on the concrete properties as a novel approach in the RCA treatment process. Furthermore, this chapter will investigate the suggested approach of coating the RCA with SF by measuring its porosity to compensate for the air voids in the RCA. This chapter will investigate the coarse RCA first and then will cover the fine RCA.

6.2. Recycled concrete aggregates (coarse)

After crushing the Kelly blocks for the coarse aggregate part of this chapter, the RCA aggregates were sieved into 20 mm and 10 mm sizes (Figure 6.1).

Figure 6.1 20 and 10 mm RCA

In Figure 6.2 it is clear that there is a difference in the surface of normal aggregate compared to recycled concrete aggregate because hardened cement paste and pores are visible on the surface of the recycled aggregates. Sieve analysis results for RCA and normal aggregates are displayed in Figure 6.3 from which it may be concluded that their particle size distributions are similar.

Figure 6.2 a) normal aggregates, b) recycled concrete aggregates

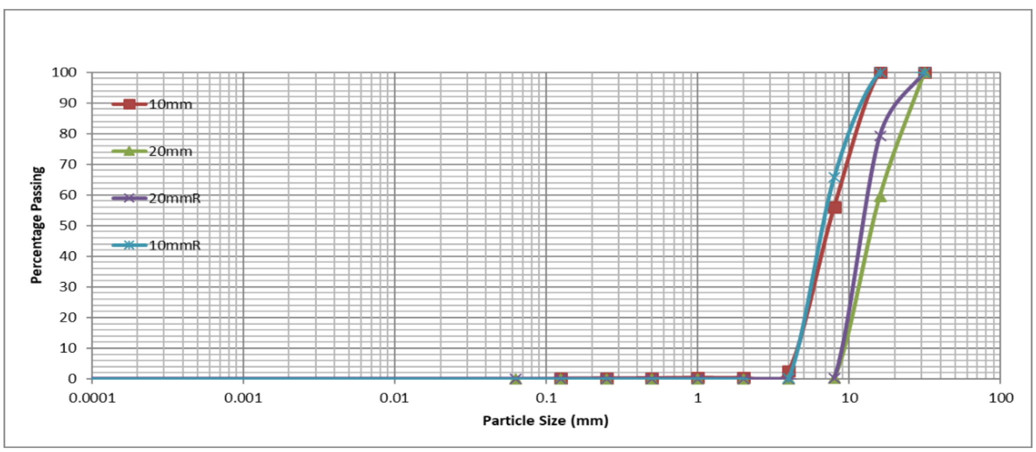


Figure 6.3 RCA sieve analysis, R= recycled aggregate

6.2.1. Recycled concrete aggregate mix

A reference mix (C30/37) was designed as an S3 slump class concrete and was prepared with a water-to-cement ratio (W/C) of 0.5, as described in Chapter 3. All mixes were compared with the base limestone mixes in term of workability, density, elastic modulus, and compressive strength. Table 6.1 shows the constituents of the reference mixes where two separate batches were made for each pour for repeatability purposes. For each pour, a total of 15 cylinders and 4 cubes were cast. The cubes were included to ensure that the two batches match in terms of 28-day compressive strength. Five cylinders were tested respectively on 7, 28 and 56 days for strength and elastic modulus.

Table 6.1 Recycled concrete aggregate mix

Mix	Note	N aggregates		Normal Sand	RCA		Cement	Water
		20mm	10mm		20mm	10mm		
RC	Reference concrete mix	700 kg/m^3	350 kg/m^3	700 kg/m^3			400 kg/m^3	200 L/m^3
RCA-35MPa	35MPa Recycled aggregates			700 kg/m^3	700 kg/m^3	350 kg/m^3	400 kg/m^3	200 L/m^3
RCA-50MPa	50MPa Recycled aggregates			700 kg/m^3	700 kg/m^3	350 kg/m^3	400 kg/m^3	200 L/m^3
T-RCA-35MPa	Micro silica fume pre-treated 35MPa recycled aggregates			700 kg/m3	700 kg/m^3	350 kg/m^3	400 kg/m^3	200 L/m^3
T-RCA-50MPa	Micro silica fume pre-treated 50MPa recycled aggregates			700 kg/m^3	700 kg/m^3	350 kg/m^3	400 kg/m^3	200 L/m^3
D-T-D-RCA-35MPa	35MPa recycled aggregates dried and then coated with micro silica fume and then left to dry before used			700 kg/m^3	700 kg/m^3	350 kg/m^3	400 kg/m^3	200 L/m^3
D-T-D-RCA-50MPa	50MPa recycled aggregates dried and then coated with micro silica fume, and then left to dry before used			700 kg/m^3	700 kg/m^3	350 kg/m^3	400 kg/m^3	200 L/m^3
D-T-D-RCA-PP 50MPa	50MPa recycled aggregates, particle packed, dried, and then coated with micro silica fume and then left to dry before used			770 kg/m^3	400 kg/m^3	580 kg/m^3	400 kg/m^3	200 L/m^3

6.2.2. Pre-treatment method

Illustrated in Figure 6.4 is the recommended pre-treatment method by this thesis, when using silica fume as a coating for recycled concrete aggregates. At first the recycled concrete aggregates are segregated based on their strength. Next, the aggregates are washed and cleaned from dust. Following, the aggregates are sieved to the required sizes then dried out to the lowest moister content.

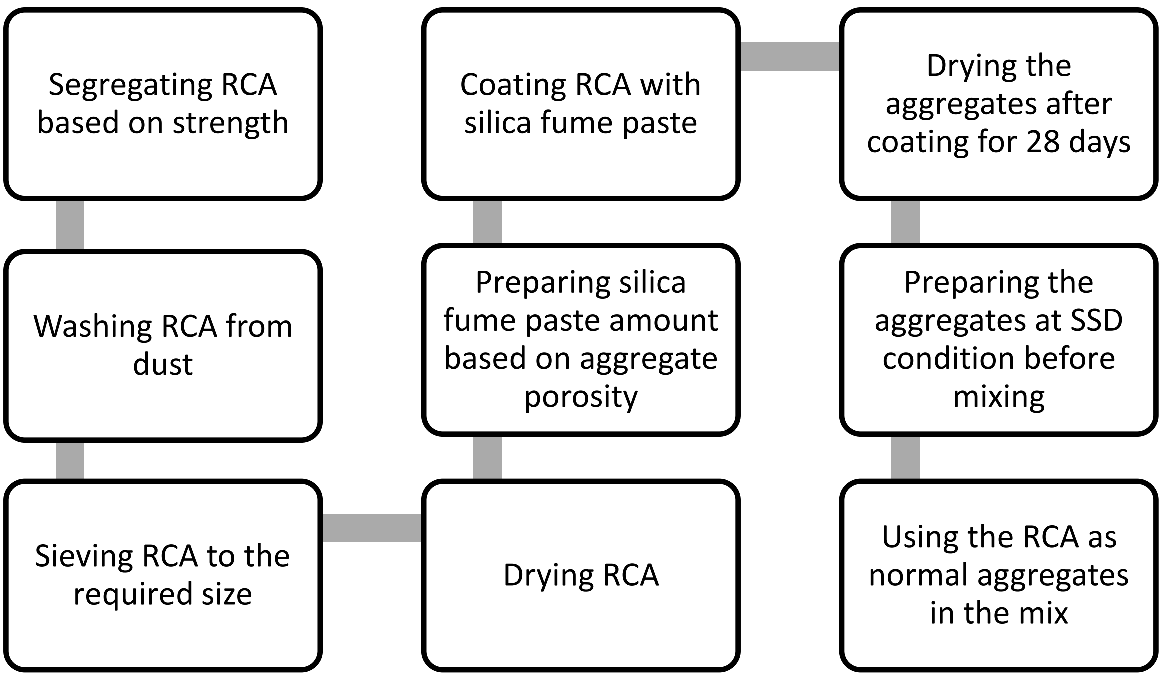


Figure 6.4 Recommended pre-treatment method

Next, silica fume is prepared separately and mixed with the aggregates (Figure 6.5). After the aggregates are left for silica fume coating to set for 28 days. Recycled concrete treated aggregates are then ready to be prepared at SSD condition and to be used as aggregates in a concrete mix. Figure 6.10 displays RCA before treatment and 28 days after treatment. It is clear that all of the surface irregularities and pores are coated with silica fume.

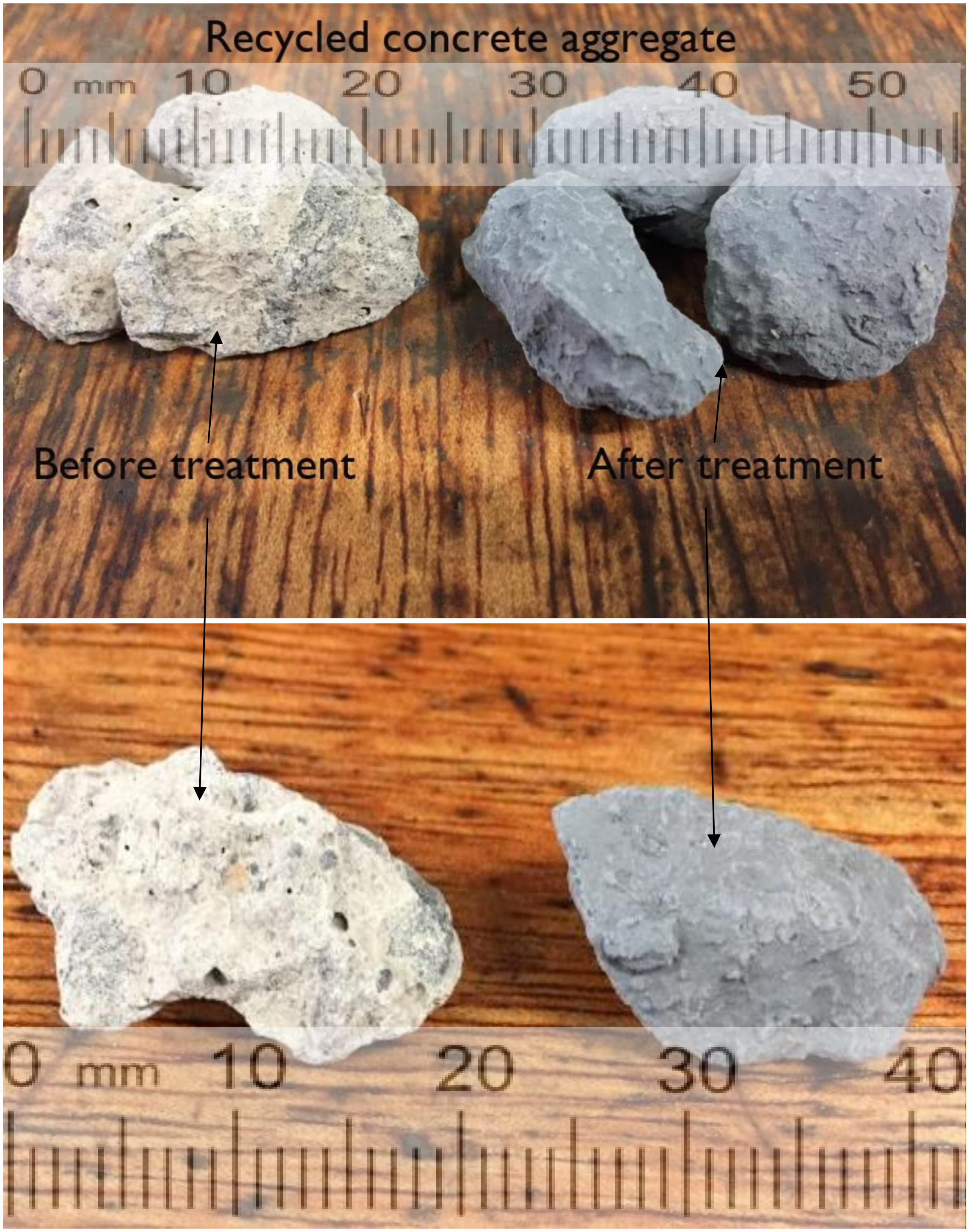


Figure 6.5 RCA before treatment and 28 days after treatment

6.2.3. **Micro silica treatment**

Recycled aggregates are batched and left to dry for 2 weeks before mixing. After that, an amount of micro silica paste is prepared based on the porosity of the aggregates test. It is prepared with a 0.80 ratio of water to micro silica, then mixed with the recycled aggregates in the mixer and left for 28 days before adding the other constituents (Figure 6.6).

Figure 6.6 The steps of coating recycled aggregates with silica fume (1) dried aggregates, (2) preparing SF, (3,4,5) coating RCA with SF, (6) leaving the coated RCA to dry, (7) final product

6.2.4. **Porosity of recycled concrete aggregate**

A porosity test was conducted on all coarse aggregates. Table 6.2 displays porosity percentage in each category. The recycled aggregates were found to be more porous than normal aggregates, as expected, due to the nature of the recycled aggregate, where it consists of normal aggregates and adhered cement paste/mortar, as shown in Figure 6.7.

For the 10 mm RCA, 35 MPa there was a 33% decrease in porosity after the dry-coat-dry treatment, which is considerably better than the 16% porosity decrease when coating with micro silica without the pre/after drying. Also, 50MPa recycled concrete aggregates displayed a 35% decrease in porosity after the dry-coat-dry suggested treatment, this is also compared to the 17% porosity decrease when coating with micro silica without the pre/post drying.

These figures are similar for the 50MPa RCA case, with corresponding decreases of 33 and 20%, and 35 and 21% respectively for the two methods of coating.

Table 6.2 Porosity test of NA: normal aggregates, RAC: recycled concrete aggregates, T: treated aggregates with micro silica fume, D: dried.

Aggregate	10 mm	20 mm
NA	5%	4%
RCA-35MPa	18%	15%
RCA-50MPa	17%	14%
T-RCA-35MPa	15%	12%
T-RCA-50MPa	14%	11%
D-T-D-RCA-35MPa	12%	10%
D-T-D-RCA-50MPa	11%	9%

Recycled aggregates were found to be more porous, which is more notable for the 35 MPa aggregates than the 50 MPa recycled aggregates (Figure 6.8). The RCA is more porous than the reference case and the treatments with SF improves the porosity by up to 35%, which is because there are more pores on the surface of SF coating than on the surface of the parent limestone.

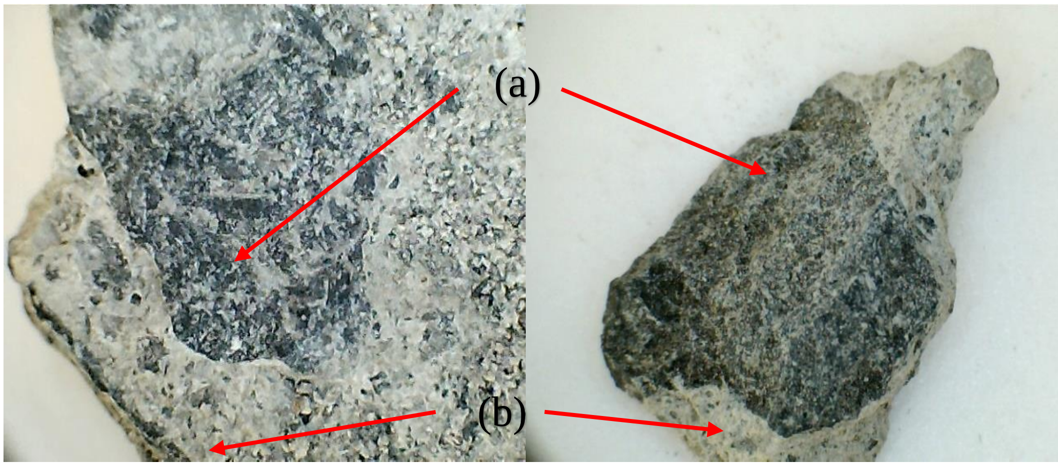


Figure 6.7 RCA, a) used normal aggregate, b) cement paste

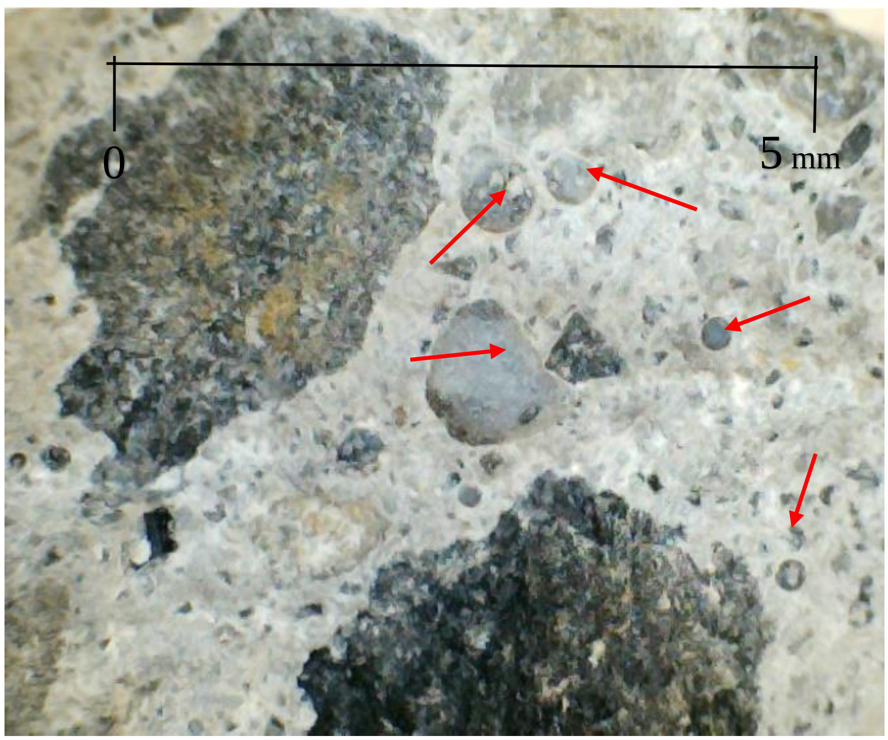


Figure 6.8 Pores on recycled concrete aggregate (shown with red arrows)

6.2.5. **Fresh concrete properties**

Slump and density tests were conducted for all concrete mixes as illustrated in Table 6.3. The reference mix was designed for an S3 slump. It is expected that the recycled aggregates will be less workable, even though they assumed to be in a saturated and surface dry condition. The dramatic decrease in workability could be related to the capillary pores size, as they are slightly bigger and more notable on the 35MPa aggregates then in the 50MPa aggregates. However, after treating both aggregate segments with micro silica fume the 35MPa regained some workability. When RCAs were dried before the pre-treatment with micro silica fume the workability did decline. However, the decrease in workability was mitigated by drying the pre-treated RCA for 28 days after the pre-treatment. That was to allow the SF to completely set and not interact with the water cement ratio when mixing the concrete.

Table 6.3 Density and slump results for RC: reference concrete mix, RCA: recycled concrete mixes, T-RCA: treated with micro silica fume recycled aggregates concrete mix, D-T-RAC: dried then treated with micro silica fume recycled aggregates concrete mix., T-RCA-PP: treated with micro silica fume recycled aggregates concrete mix and particle packed, D-T-D- RAC-PP: dried then treated with micro silica fume then dried recycled aggregates concrete mix

Mix	Density		Slump	
	Batch 1	Batch 2	Batch 1	Batch 2
RC	2380 kg/m^3	2375 kg/m^3	145 mm	150 mm
RCA-35MPa	2263 kg/m^3	2282 kg/m^3	25 mm	25 mm
RCA-50MPa	2131 kg/m^3	2188 kg/m^3	60 mm	65 mm
T-RCA-35MPa	2267 kg/m^3	2244 kg/m^3	65 mm	75 mm
T-RCA-50MPa	2206 kg/m^3	2225 kg/m^3	85 mm	90 mm
D-T-D-RCA-35MPa	2320 kg/m^3	2305 kg/m^3	50 mm	50 mm
D-T-D-RCA-50MPa	2295 kg/m^3	2280 kg/m^3	75 mm	85 mm
D-T-D-RAC-PP 50MPa	2327 kg/m^3	2343 kg/m^3	95 mm	85 mm

6.2.6. **Compressive strength**

The reference mix has a 34.3 MPa strength after 28 days. It is expected for the concrete with a 100% replacement of normal aggregates with the recycled aggregates to have a lower compressive strength. The compressive strength. Of the RCAs was lower by an 18%. However, Pre-treating the recycled aggregates with SF, was found to increase the concrete strength by 7%. As shown in Figure 6.9, and Table 6.4. Both types of recycled concrete aggregate mixes showed a better improvement from 7% to 9% with the SF pre-treatment. Furthermore, when recycled concrete aggregates were dried before the SF pre-treatment the compressive strength significant improved by more than 10% for both types of recycled aggregates. When 50MPa recycled concrete aggregates were dried and then pre-treated and particle parked then dried again before using the results were outstanding as the compressive strength increased by 54%. This indicates that drying recycled concrete aggregates and the coating them with SF and leaving them for 28 days to dry again is a feasible method to not only get the desired strength out of concrete made out of recycled aggregates but to even exceed the reference concrete mix. This is because the SF soaks better into the pores of the RCA if it is not SSD. And this is the objective of the suggested novel treatment process that this chapter illustrates.

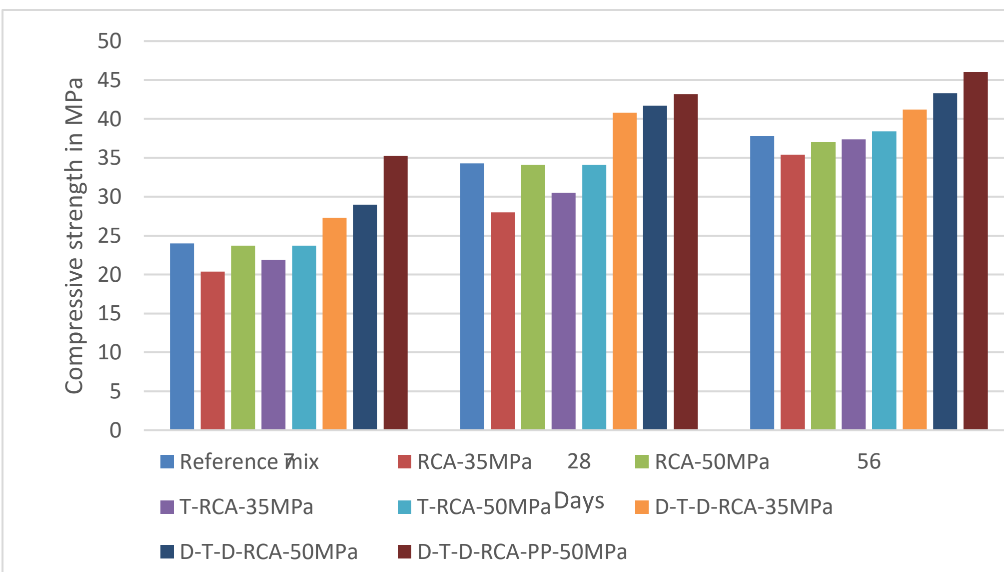


Figure 6.9 RCA mixes compressive strength

Table 6.4 RCA Compressive strength results

Day	Compressive strength in MPa															
	Reference mix	Average	RCA-35MPa	Average	RCA-50MPa	Average	T-RCA-35MPa	Average	T-RCA-50MPa	Average	D-T-D-RCA-35MPa	Average	D-T-D-RCA-50MPa	Average	D-T-D-RCA-PP-50MPa	Average
	24.5		20		22		22.1		24.1		27		29		33.2	
	21.5		21		23		21.8		23.5		26		29		34.7	
7	23.5	24	20.5	20.4	23	22.9	21.9	21.9	22.9	23.7	29	27.3	30.5	29.0	36.5	35.24
	25		21.5		23		22		23.8		25.5		28		36	
	25.5		19		23.5		21.8		24		29		28.7		35.8	
	35.5		28		33		30		34.5		40		40.5		42	
	34		28		29		31.2		33.9		41		42		44.5	
28	35	34.3	28.5	28.0	31	31.6	29.8	30.5	33.8	34.1	40	40.8	40	41.7	43.6	43.18
	33		27.5		32		30.8		34		41.5		42.5		43	
	34		28		33		30.7		34.2		41.5		43.5		42.8	
	39		36		38		37		39		41		42.5		46	
	38		36		37		37.4		38.5		40		43.5		45.8	
56	37	37.8	34.5	35.4	35	36.6	38	37.4	38	38.4	41.5	41.2	44	43.3	46.5	46.04
	36.5		36		36		36.9		38.2		41.5		44		45.2	
	38.5		34.5		37		37.7		38.4		42		42.5		46.7	

6.2.7. Elastic modulus

The reference mix elastic modulus after 28 days is 28 GPa. The elastic modulus results of treated mixes are represented in Table 6.5. The average elastic modulus did increase by 22% after the recycled aggregate pre-treatment with the SF. That is a strong indication that SF is improving the aggregate's mechanical properties in RCA concrete.

Table 6.5 Average elastic modulus after 28 days

Mix	7 days	28 days	56 days
Reference mix	23.1 GPa	28.0 GPa	29.3 GPa
RCA 35 MPa	20.2 GPa	24.8 GPa	25.1 GPa
RCA 50 MPa	21.4 GPa	28.1 GPa	28.7 GPa
T-RCA 35 MPa	20.4 GPa	28.2 GPa	29.5 GPa
T- RCA 50 MPa	22.5 GPa	33.0 GPa	33.2 GPa
D-T-D - RCA-35 MPa	21.8 GPa	29.0 GPa	29.9 GPa
D-T-D - RCA-50 MPa	24.8 GPa	33.8 GPa	35.3GPa
D-T-D - RCA-PP 50 MPa	25.4 GPa	34.1 GPa	35.2GPa

6.3. Recycled concrete aggregates (fine)

This part illustrates the effects of adding fine recycled concrete aggregates (recycled sand) as collected from the same recycled aggregate batch (Figure 6.10), which resembles the fine waste part of the recycled concrete aggregates.

Figure 6.10 Fine recycled concrete aggregate (recycled sand)

In Figure 6.11 the RCA sieve analysis is displayed. The graph shows the difference in partial size distribution between normal sand and recycled sand. It is clear from the particle size distribution chart that the recycled aggregates are coarser than normal sand.

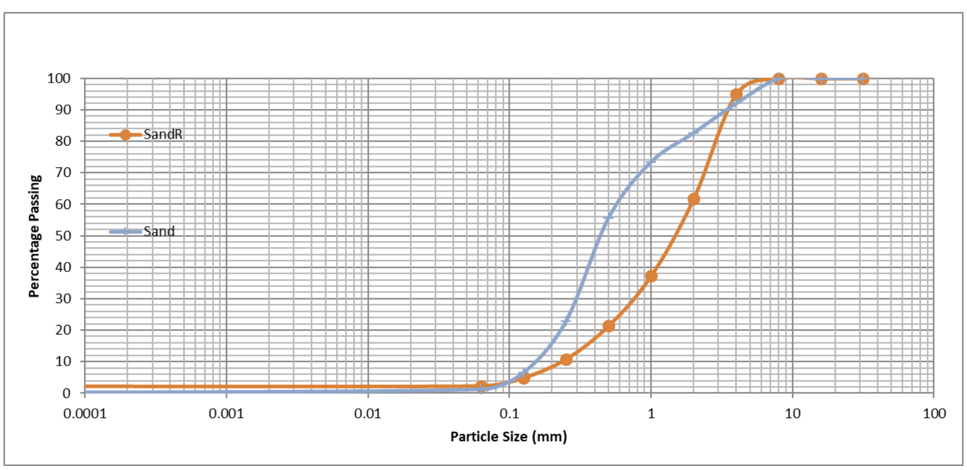


Figure 6.11 Fine RCA sieve analysis, SandR: recycled sand, Sand: normal sand

6.3.1. **Treatment with silica fume**

Recycled sand was dried and then coated with SF, where the amount of silica fume was gradually increased until the recycled sand reached a level of saturated surface dry based on ASTM C 128 standard (ASTM-International, 2015). Table 6.6 shows the amount of SF added on each mix. This amount is added based on trial and error. SF was added until it passed the saturated surface dry condition mentioned in the standard.

Table 6.6 Amount of silica fume in each mix

Mix	Silica fume
RSF5	5%
RSF10	10%
RSF20	20%

Figure 6.12 displays the coating of the recycled sand with three different amounts of SF and the deployment of the fine aggregate saturated surface dry test. It is clear that there was nothing to observe when 5 % SF was added as it scarcely changed the status of the dry recycled sand. However, adding silica fume with 10% replicates the saturated surface dry condition for fine aggregates. Furthermore, when 20% of SF was added to the recycled sand it fails the saturated surface dry sand test by being over saturated.

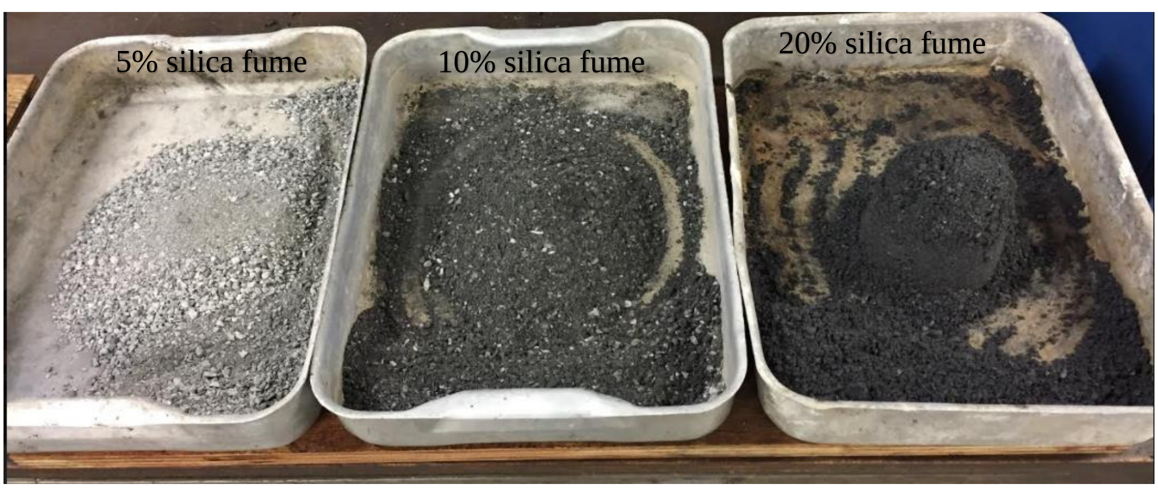


Figure 6.12 Recycled sand after coating with silica fume

6.3.2. **Mortar testing**

Mortar prism tests were conducted to examine the ability of the SF treatment to regain the strength of the mortar, for this test 4 mixes were designed as displayed in Table 6.7, for each mix a set of 6 prisms (40*40*160) mm were cast to get 3 flexural test results and 6 compressive strength for 7 and 28 days (Figure 6.13).

Table 6.7 Mortar design for recycled sand mixes S: normal sand, RS5: recycled sand 5% silica fume, RS10: recycled sand 10% silica fume, RS20: recycled sand 20% silica fume

Mix	Sand	Recycled Sand	Silica fume
S	100%	-	-
RS5	-	100%	5%
RSF10	-	100%	10%
RSF20	-	100%	20%

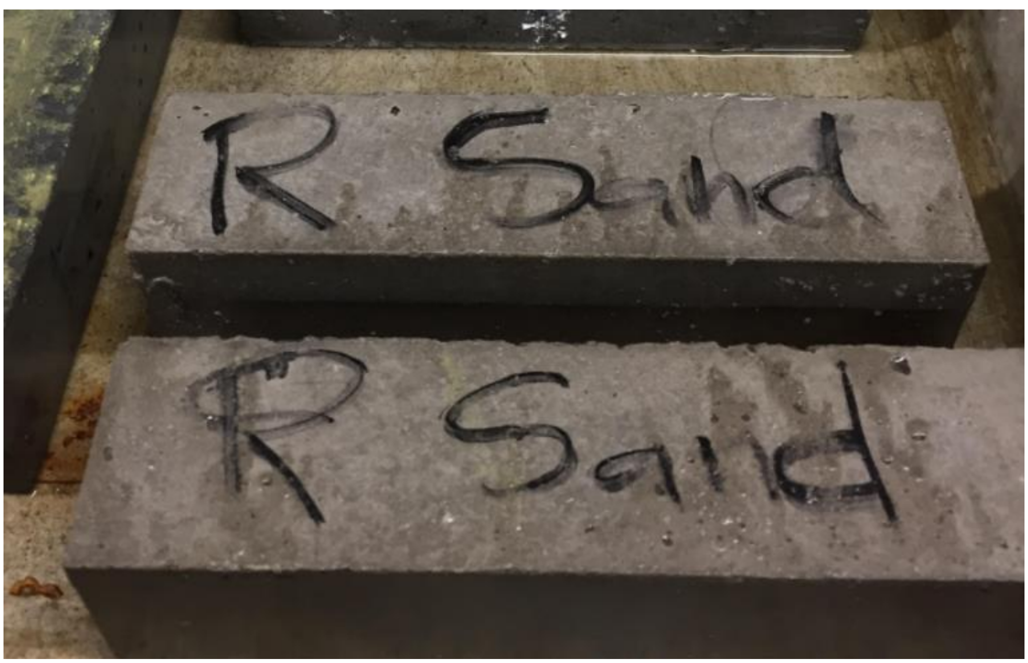


Figure 6.13 Recycled sand mortar prisms

6.3.3. Mortar flexural strength

Prisms were tested in accordance with I.S. EN 12390-6, Testing hardened concrete, Part 6 for flexural after 7 and 28 days (Figure 6.14). The untreated recycled sand is significantly lower by 20% than the reference mix. The 10% treated mix in flexural strength is almost the same as the reference mix at 28 days. Even though, it was lower by 18% than the reference mix when tested at 7 days this due to the deference in hardening time between PC, GGBS and SF (Figure 6.15).

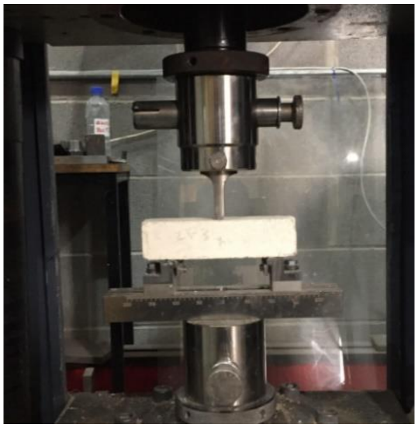


Figure 6.14 Prisms flexural test

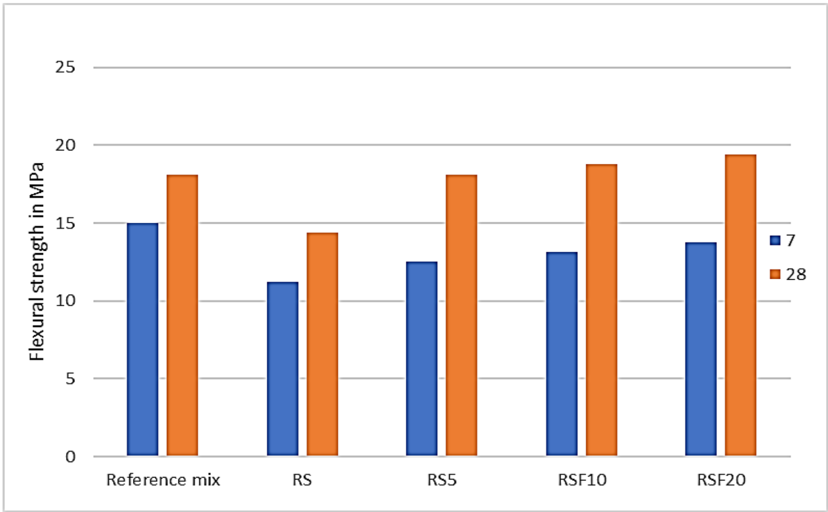


Figure 6.15 Prisms flexural strength for S: normal sand, RS5: recycled sand 5% silica fume, RS10: recycled sand 10% silica fume, RS20: recycled sand 20% silica fume

6.3.4. **Mortar compressive strength**

Prisms were tested for co For the 10% silica fume treated recycled sand the compressive strength the mix was very close to the reference mix at 30 MPa after 28 days. However, for the 20% SF treated recycled sand specimen exceeded the reference mix by a 10% in terms of compressive strength. However, it was more than saturated with SF paste according to the standard (ASTM-International, 2015). so extra SF may act as a strength enhancer (Figure 6.16).

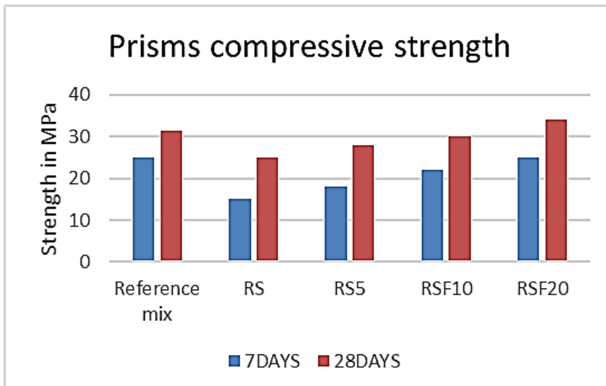


Figure 6.16 Prisms compressive strength for S: normal sand, RS5: recycled sand 5% silica fume, RS10: recycled sand 10% silica fume, RS20: recycled sand 20% silica fume

6.3.5. **Recycled sand concrete mix**

For this part of the research four concrete mixes were designed as displayed in Table 6.8. The recycled sand with 5% silica fume was not included in this part due to its low compressive strength in the previous test.

Table 6.8 Recycled sand concrete mix design, F.A.D. = Fresh Average density

Mix	**Note**	**N aggregates**		**Normal Sand**	**SF**	**RCA Sand**	**Cement**	**Water**	**F.A.D.**
		20mm	**10mm**						
RC	Reference concrete mix	708 kg/m³	355 kg/m³	707 kg/m³	-	-	404 kg/m³	202 L/m³	2377 kg/m³
RS	Not treated	600 kg/m³	200 kg/m³	-	-	700 kg/m3	400 kg/m³	200 L/m³	2108 kg/m³
RSF10	10% treated with silica fume	650 kg/m³	325 kg/m³	-	40 kg/m³	700 kg/m³	400 kg/m³	200 L/m³	2322 kg/m³
RSF20	20% treated with silica fume	658 kg/m³	330 kg/m³	-	82 kg/m³	708 kg/m³	406 kg/m³	203 L/m³	2387 kg/m³

6.3.6. **Fresh concrete properties**

When normal sand was replaced with 100% recycled sand the slump clearly decreased (Table 6.9). That is because of the extra porosity of the recycled sand. The density was also seen to decrease for the same reason. However, slump did increase when recycled sand was treated with SF. Density also did increase gradually for the treated mixes

Table 6.9 Fresh concrete properties

Mix	Density		Slump	
	Batch 1	Batch 2	Batch 1	Batch 2
RC	2380 kg/m^3	2375 kg/m^3	145 mm	150 mm
RS	2098 kg/m^3	2119 kg/m^3	25 mm	20 mm
RSF10	2315 kg/m^3	2329 kg/m^3	45 mm	50 mm
RSF20	2390 kg/m^3	2385 kg/m^3	55 mm	50 mm

6.3.7. **Compressive strength**

For the concrete compressive strength, it was expected the strength of concrete will drop after replacing the normal sand with recycled sand from the sieve analysis results illustrated at the beginning of this chapter. In Table 6.10 and Figure 6.19 it is displayed that the concrete strength did increase after the SF treatment. There was a difference between the RSF10 and RSF20 in terms of compressive strength and that is due to the extra amount of SF in the treatment phase. Even though, at 28 days treated recycled sand with 10% SF is lower than the reference mix by about 5%, yet this decrease in strength was compensated when recycled sand was used with recycled concrete aggregates. This is illustrated later in Chapter 8.

Table 6.10 Recycled sand compressive strength

Day	Compressive strength in MPa							
	Reference mix	Average	RS	Average	RS10	Average	RS20	Average
7	24.5	24	17	17.9	23	22.9	25.5	24.7
	21.5		18		22		24.5	
	23.5		18.5		23.5		25	
	25		17		24		24	
	25.5		19		22		24.5	
28	35.5	34.3	25.5	26.6	31	32.2	36	35.0
	34		26		33.5		34.5	
	35		26		32		34	
	33		28		32		35	
	34		27.5		32.5		35.5	
56	39	37.8	30	29.0	36	36.7	37.5	38.8
	38		29.5		37		39	
	37		28.5		36.5		40	
	36.5		28		36		39.5	
	38.5		29		38		38	

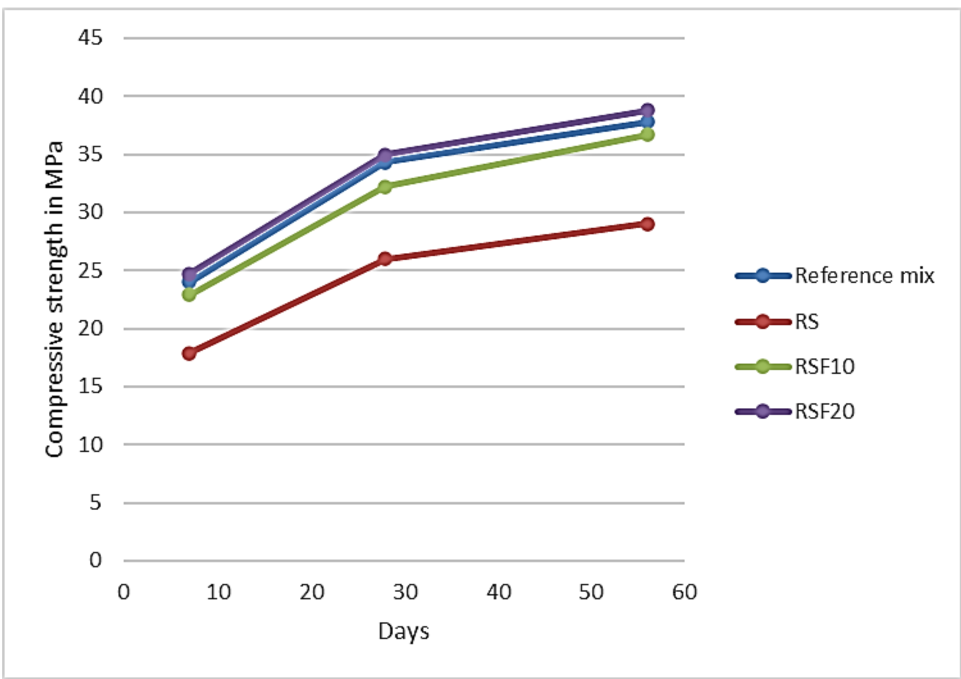


Figure 6.17 Recycled sand compressive strength

6.3.8. **Elastic modulus**

Recycled sand concrete has a low modulus of elasticity. However, when treated with SF the modulus of elasticity increased in line with the amount of silica fume added to treat the recycled sand. That could be due to the geopolymer (SF) effect on the elastic modulus. Modulus of elasticity results are displayed in Table 6.11.

Table 6.11 Elastic modulus results

Mix	7 days	28 days	56 days
Reference mix	23.1 GPa	28.0 GPa	29.3 GPa
RS	19.2 GPa	24.7 GPa	25.0 GPa
RSF10	20.0 GPa	25.9 GPa	26.0 GPa
RSF20	21.5 GPa	26.3 GPa	28.1 GPa

6.4. **Conclusions**

The following conclusions may be drawn from this chapter:

- Micro silica is to be mixed as a paste separately with a 0.80 ratio of water to SF, prior to mixing with the recycled aggregates.
- Pre-treating recycled aggregates with SF improves the workability of RCA concrete. This is due to the reduction in the recycled aggregate's porosity after treatment because the micro silica small particles can fill the surface capillary pores.
- This pre-treatment method has a significant effect in increasing the concrete strength as both treated types of recycled aggregate showed an increase in strength.
- Drying the RCA before treating them with micro silica fume significantly improved the compressive strength of the concrete because the penetration of the SF was better and so it was a more effective coating in reducing the water absorption on the RCA surface.
- The 35MPa dried RAC pre-treated mix increased by 36% in strength.
- The 50MPa dried RAC showed a 45% increase in strength after pre-treating the aggregates with SF.

- The 50MPa dried RCA showed more than 50% increase in compressive strength from the original RCA. This increase in strength was gained after pre-treating the aggregates with SF and particle packing the aggregate.
- It is recommended to leave the recycled aggregates for 28 days after treatment for SF to completely set.
- Treating fine recycled concrete aggregate (recycled sand) with SF regains part of the concrete's workability.
- In recycled sand the difference between 20% treatment and 10% treatment with SF is not remarkable when it comes to density and workability. However, compressive strength did undoubtedly increase more with 20% than 10% after treatment with SF.
- The (Dry-Treat -Dry) method suggested in this chapter to compensate for the compressive strength loss did work effectively. Furthermore, it improved the overall compressive strength by 50% which exceeded the reference mix by 26%.
- There was a difference between the RSF10 and RSF20 in terms of compressive strength and that is due to the extra amount of silica fume in the treatment phase. Even though, at 28 days treated recycled sand with 10% is lower in strength than the reference mix by about 5%, yet this decrease in the compressive strength was compensated when recycled sand was used with recycled concrete aggregates.

Chapter 7

Ground granulated blast furnace slag (GGBS)

7. Ground granulated blast furnace slag

7.1. Objective

The objective of this chapter was to replace 100% of the Portland cement with GGBS and silica fume in a concrete mix. This is only possible by activating the GGBS using a recycled alkaline activator, where conventional sodium and potassium-based activators are not recycled materials. Therefore, in this thesis, the novel application of lithium hydroxide (LH) and lithium chloride (LC) as recycled alkaline activators will be explored. To achieve this objective, it was important to test the paste first to get a full understanding of the efficacy of the suggested recycled alkaline activators. The second stage was to test this novel activated paste in a concrete mix.

7.2. Mortar testing

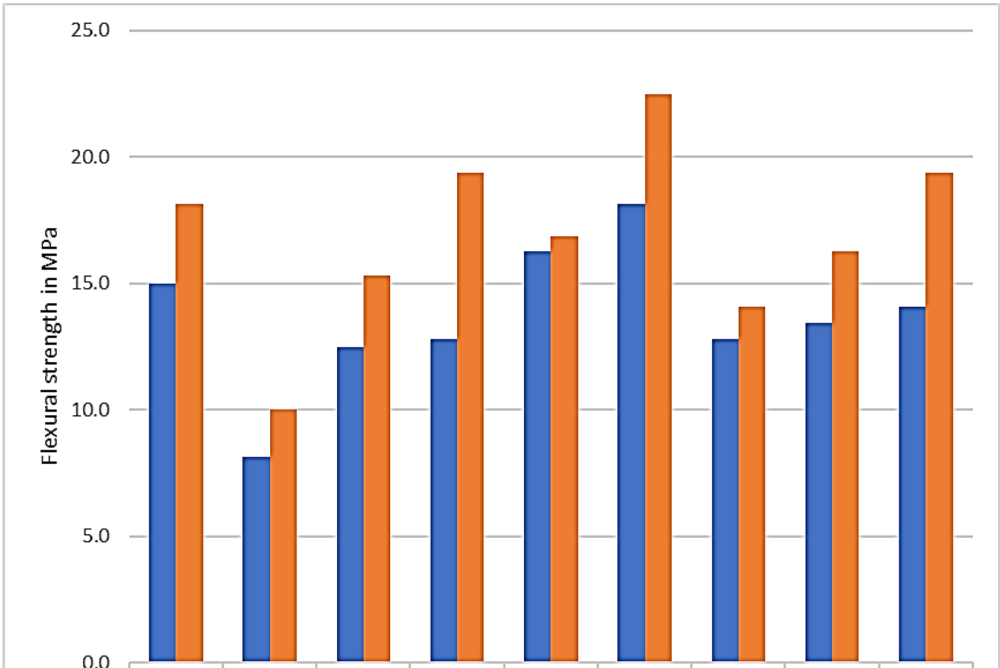
Mortar prism flexural and compressive tests were conducted to examine the full replacement of Portland cement with GGBS, where the nine mixes were mixed at a proportion of 1: 3: 0.5 cement to sand to water and designed as displayed in Table 7.1. The recycled activator is added by percent of the total cementitious material. For each mix a set of 6 prisms (40*40*160mm) were cast to get 3 flexural test results and 6 compressive strengths for 7 and 28 days. This test aims to examine the effect of using the suggested recycled activators LC and LH on the compressive and flexural strengths of a mix that has 0% of Portland cement (CEM IIA-L). The concrete reference mix is added for display only.

Table 7.1 GGBS prisms mixes GGBS: granulated blast furnace slag, SF: silica fume, C: Portland cement, LC: lithium chloride, LH: lithium hydroxide, 10: 10%, 20:20%

Mix	cement	GGBS	Silica fume	Water	Sand	Activator	
						lithium chloride	lithium hydroxide
Reference mix	1000 g	-	-	500 mL	9000 g	-	-
GGBS/SF	-	800 g	200 g	500 mL	9000 g	-	-
GGBS/SF/C	100 g	700 g	200 g	500 mL	9000 g	-	-
GGBS/SF/LC	-	800 g	200 g	500 mL	9000 g	100 g	-
GGBS/SF/LH	-	800 g	200 g	500 mL	9000 g	-	100 g
GGBS/SF/C/LC+LH10	100 g	700 g	200 g	500 mL	9000 g	50 g	50 g
GGBS/SF/LC+LH5	-	800 g	200 g	500 mL	9000 g	25 g	25 g
GGBS/SF/LC+LH10	-	800 g	200 g	500 mL	9000 g	50 g	50 g
GGBS/SF/LC+LH20	-	800 g	200 g	500 mL	9000 g	100 g	100 g

7.3. Mortar flexural strength

Prisms were tested in flexure after 7 and 28 days (Figure 7.1). Even though concrete is weak in flexure, however this test gives an understanding on how GGBS and SF flexural strength is affected by the presence of increasing quantities of lithium as an alkaline activator. It was predicted and tested that GGBS without activator will have the lowest flexural results as it is a latent hydraulic binder. Interestingly with the addition of the recycled activators the flexural strength increases respectively with an increment in the alkaline activator. Comparing to the one with no activators there was a 90% increase in flexural strength. When cement was added at a rate of 10% the increase in strength after 28 days was about 120%. However, the aim of this thesis is not to use cement in forming the concrete, so this result was only for comparison reasons.



	Reference mix	GGBS/SF	GGBS/SF /C	GGBS/SF /LC	GGBS/SF /LH	GGBS/SF /C/LC+LH	GGBS/SF /LC+LH5	GGBS/SF /LC+LH10	GGBS/SF /LC+LH20
7	15.0	8.1	12.5	12.8	16.3	18.1	12.8	13.4	14.1
28	18.1	10.0	15.3	19.4	16.9	22.5	14.1	16.3	19.4

Figure 7.1 GGBS prisms flexural strength results in MPa. GGBS: granulated blast furnace slag, SF: silica fume, C: Portland cement, LC: lithium chloride, LH: lithium hydroxide, 10: 10%, 20:20%

7.4. Mortar compressive strength

The same prisms were subsequently tested for compressive strength after 7 and 28 days. The non-activated GGBS mix had the lowest compressive strength which was expected. There was a 500% increase in the 28 days strength when 5% recycled activators were added compared to the equivalent non-activated mix. Moreover, this increased to 900 % when 20% of the recycled activators were used. When the alkaline activators amount was increased, the strength of the GGBS increased correspondingly. By adding 20% alkaline activator to the GGBS it performed in compression like the reference mix after 28 days, despite the 7-day strength of GGBS being lower, which is expected for the slower reacting GGBS (Figure7.2). This work confirms that the proposed lithium based recycled activators work as GGBS and silica fume activators.

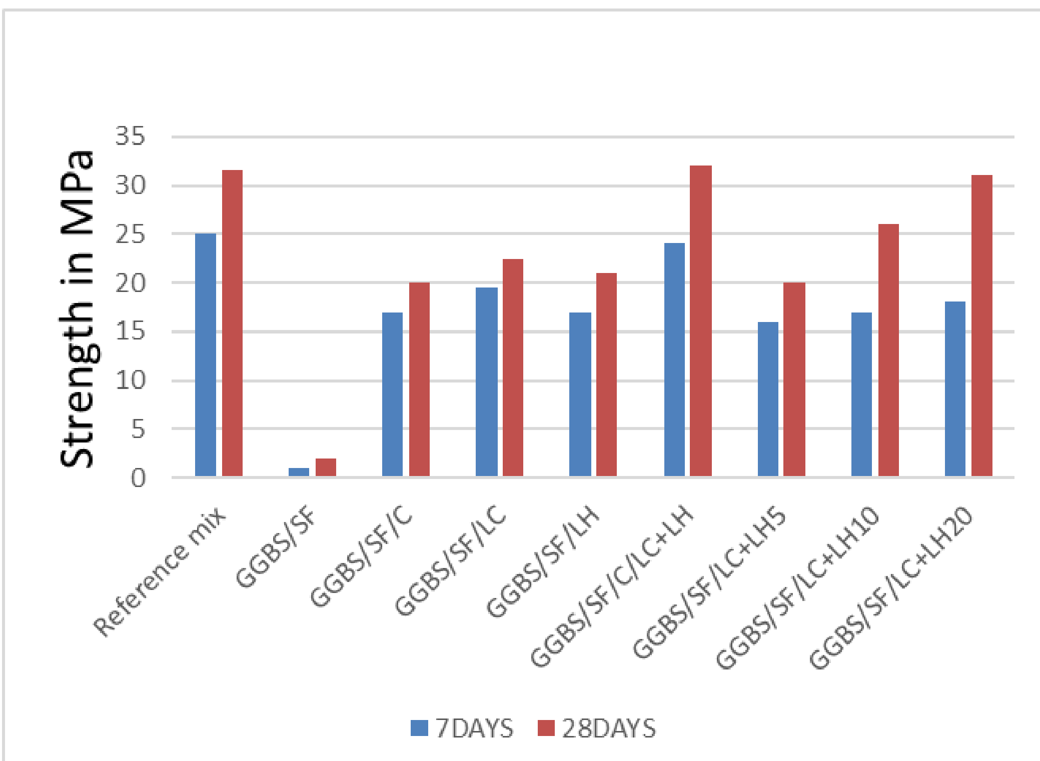


Figure 7.2 GGBS prisms compressive strength results in MPa. GGBS: granulated blast furnace slag, SF: silica fume, C: Portland cement, LC: lithium chloride, LH: lithium hydroxide, 10: 10%, 20:20%

7.5. **GGBS concrete mix**

This part of the research examines concrete compressive strength for the best mortar mix from Section 7.4. Additionally, this same mix is also subjected to the particle packing method illustrated in Chapter 4, where concrete mixes were designed as displayed in Table 7.2. The GGBS/SF/LC+LH20 mix was selected as the best mortar mix in compression strength performance in the previous test.

Both of the GGBS mixes have 0% Portland cement and are activated by recycled lithium base activators: lithium chloride 10 % and lithium hydroxide 10% of the total mass of the cementitious material required.

Table 7.2 GGBS concrete mixes

Mix	Note	N aggregates		Sand	Silica fume	GGBS	Cement	LC	LH	Water
		20mm	10mm							
Reference mix	Reference concrete mix	700 kg/m^3	350 kg/m^3	700 kg/m^3	-	-	400 kg/m^3	-	-	200 L/m^3
GGBS/SF/LC+LH20	GGBS 80% SF 20%	700 kg/m^3	350 kg/m^3	700 kg/m^3	80 kg/m^3	320 kg/m^3	-	40 kg/m^3	40 kg/m^3	200 L/m^3
GGBS/SF/LC+LH20PP	GGBS 80% SF 20% Particle packed	400 kg/m^3	580 kg/m^3	770 kg/m^3	80 kg/m^3	320 kg/m^3	-	40 kg/m^3	40 kg/m^3	200 L/m^3

7.6. Fresh GGBS concrete properties

When Portland cement was replaced with GGBS and silica fume the slump value decreased, as may be observed from Table 7.3 However, this was compensated for when aggregates were particle packed because the workability did increase slightly which could be due to the marginal increase in density.

Table 7.3 GGBS fresh properties

Mix	Density		Slump	
	Batch 1	Batch 2	Batch 1	Batch 2
Reference mix	2380 kg/m^3	2375 kg/m^3	145 mm	150 mm
GGBS/SF/LC+LH20	2016 kg/m^3	2004 kg/m^3	75 mm	70 mm
GGBS/SF/LC+LH20PP	2140 kg/m^3	2172 kg/m^3	80 mm	80 mm

7.7. GGBS compressive strength

It is observed from Table 7.4 and Figure 7.3 that GGBS/SF/LC+LH20 mix also matched the control mix strength at 28d days. However, it increased by more than 15% on the 56 days compressive strength result. Furthermore, when aggregates in the GGBS mix were particle packed the compressive strength at 28 days increased by a further 11%. Thus, the effect of aggregate particle packing is significantly observable on the strength of concrete. These compressive strength results are in compliance with Korde et al. (2019) work on 35%, 50% and 75% replacement of cement with GGBS in a concrete mix (Figure 7.4).

Table 7.4 GGBS compressive strength

Day	Compressive strength in MPa					
	Reference mix	Average	GGBS/SF/LC+LH20	Average	GGBS/SF/LC+LH20PP	Average
7	24.5	24	21	21.0	22	21.8
	21.5		20		21.5	
	23.5		21.5		21	
	25		22		22.5	
	25.5		20.5		22	
28	35.5	34.3	35	34.6	39	38.1
	34		33.5		37	
	35		36		37.5	
	33		34		39	
	34		34.5		38	
56	39	37.8	42	42.4	45	44.1
	38		43.5		44	
	37		41		43	
	36.5		42.5		44.5	
	38.5		43		44	

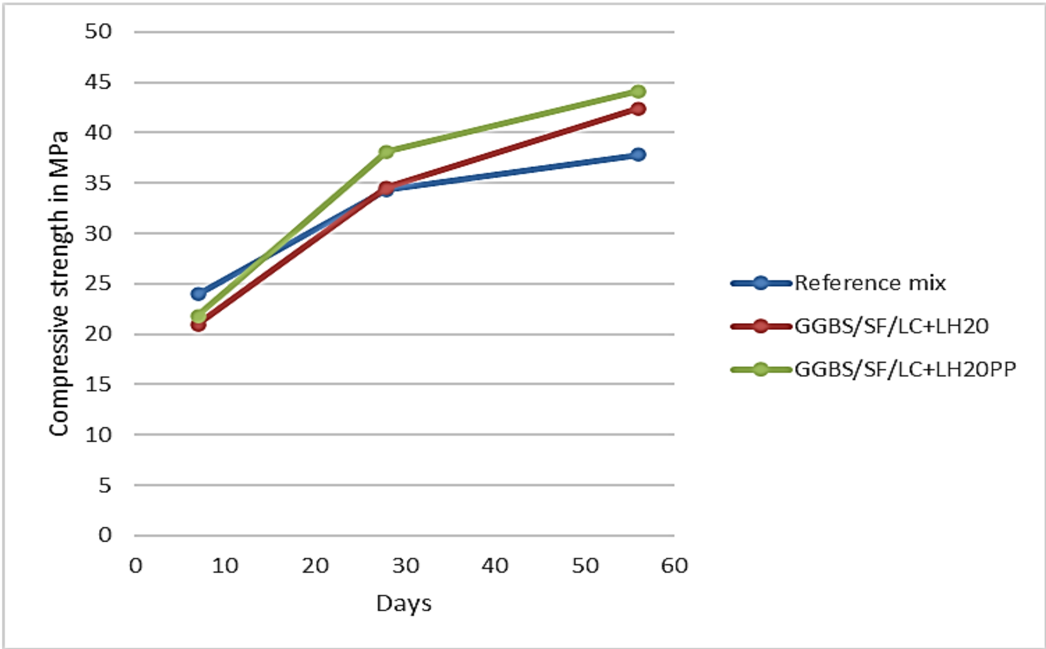


Figure 7.3 GGBS compressive strength, GGBS: granulated blast furnace slag, SF: silica fume, LH: lithium hydroxide, LC: lithium chloride PP: particle packing, 20:20%

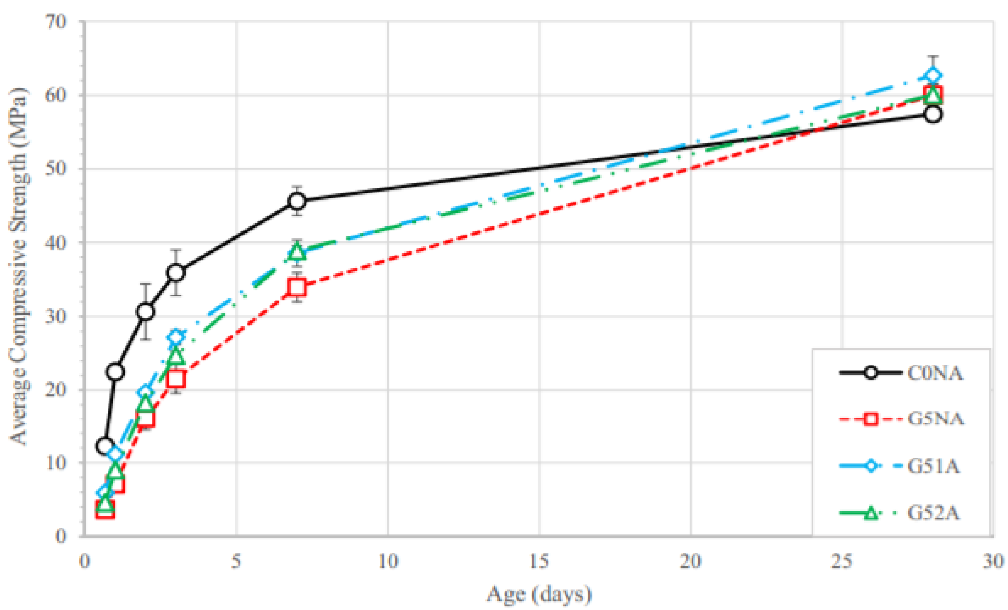


Figure 7.4 Relationship between CEM I 42.5 R and GGBS compressive strengths and age with and without admixtures for 50% slag at ambient temperature (Korde et al., 2019)

This successfully demonstrates that a 100% recycled cement concrete can be activated by a new recycled activator with comparable compressive strength at 28 days.

7.8. GGBS elastic modulus

The reference mix elastic modulus result after 28 days was 28.0 GPa. The elastic modulus results of treated mixes are represented in Table 7.5. the elastic modulus had a noteworthy improvement when replacing portolan cement with GGBS/silica fume because the geopolymer elastic modulus increased by 17% at 28 days. And when GGBS mix was particle packed the elastic modulus increased by 25%. This same observation was concluded by Xie et al. (2019) in his research. Finally, a 100% non-PC concrete can have a similar E value as a PC concrete using Lithium to activate the GGBS/SF. This will have relevance for the serviceability limit state criteria, including deflections, crack widths and creep.

Table 7.5 GGBS elastic modulus results

Mix	7 days	28 days	56 days
Reference mix	23.1 GPa	28.0 GPa	29.3 GPa
GGBS/SF/LC+LH20	25.3 GPa	32.8 GPa	34.1 GPa
GGBS/SF/LC+LH20PP	28.4 GPa	34.8 GPa	34.8 GPa

7.9. Conclusions

The objective of this chapter was to fully replace Portland cement with GGBS and SF, and to use a lithium based recycled alkaline activator to activate the GGBS and SF, lithium being a wholly recycled material. The following conclusions may be drawn from this chapter:

- There was a 500% increase in the 28 days strength when 5% recycled activators were added compared to the equivalent non-activated mix. Moreover, this increased to 900 % when 20% of the recycled activators were used.
- Lithium chloride LiCl and lithium hydroxide LiOH have been demonstrated to be successful as activators for the GGBS and silica fume cementitious mixture.

- Activated GGBS/silica fume binder with LiCl and LiOH has a significant positive effect in increasing the elastic modulus by 22% and compressive strength by 11%.
- When using GGBS it is expected that the reaction will not be as fast as for normal concrete. However, with the suggested recycled lithium activators the strength at the 28th day is reliably determined to be the same as normal concrete.
- Greater strength and marginal slump values can be achieved by particle packing the aggregates for the GGBS/silica fume mix.
- This chapter illustrated that concrete compressive strength can be achieved without using Portland cement by using 80% GGBS, 20% silica fume and wholly recycled lithium activators.

Chapter 8

Combination mix

8. Combination mix

8.1. Objective

The objective of this chapter was to combine all of the gained knowledge from the previous chapters to design a novel concrete mix that is solely made from recycled and by-product materials in a uniquely sustainable concrete mix. Furthermore, it is the intention to improve the strength of this novel mix by applying the aggregate particle packing theory so that strength losses due to the inclusion of waste materials could be minimised. The aim of this chapter is to examine the combined effect of the conclusions from the individual research investigations into one holistic approach to achieving a viable 100% recycled mix, as follows:

- 100% sulfuric acid treated recycled chipped rubber (Chapter 5)
- Waste 6.3 mm aggregates (Chapter 5)
- 100% dried - treated with SF – dried recycled concrete aggregates (Chapter 6)
- Recycled sand treated with SF from (Chapter 6)
- 1005 cement replacement with activated GGBS and silica fume (Chapter 7)
- Recycled activators LC and LH (Chapter 7)
- Particle packing (Chapter 4)

Moreover, the substitution of normal tap water with 100% rainwater was investigated and is included in the mixing table for this chapter. Rainwater was harvested as recommended by Gikas and Tsihrintzis (2017) as discussed in section 2.6.1 in chapter 2.

8.2. Sustainable concrete mix

In this part of the research seven concrete mixes were designed as displayed in Table 8.1. the mixes include a full replacement of the Portland cement, aggregate, sand, and water. The research investigates the replacement of normal tap water with 100% rainwater by combining the recycled, and by-product constituents with: (a) recycled concrete aggregate (Series S1) and (b) treated chipped rubber (Series S2). After that both are particle packed as a final improvement for the sustainable concrete mixes (labelled S1PP and S2PP, respectively).

Table 8.1 Sustainable concrete mix, RW: rainwater mix, S1: sustainable mix 1, S1PP: sustainable mix 1 particle packed, S2: sustainable mix 2, S2PP: sustainable mix 2 particle packed (a): 10% treatment of recycled sand, (b): 20% treatment of recycled sand

		Reference	RW	S1	S1PP	S2	S2PP	S2” PP
Normal aggregates	20mm	700 kg/m^3	700 kg/m^3	-	-	-	-	-
	10mm	350 kg/m^3	350 kg/m^3	-	-	-	-	-
Recycled Aggregates	20 mm	-	-	700 kg/m^3	430 kg/m^3	-	-	-
	10 mm	-	-	350 kg/m^3	620 kg/m^3	-	-	-
Chipped rubber	20 mm	-	-	-	-	250 kg/m^3	125 kg/m^3	125 kg/m^3
	10 mm	-	-	-	-	125 kg/m^3	75 kg/m^3	75 kg/m^3
6.3 mm waste aggregates		-	-	-	-	250 kg/m^3	500 kg/m^3	500 kg/m^3
Normal Sand		700 kg/m^3	700 kg/m^3	-	-	-	-	-
Recycled Sand		-	-	700 kg/m^3 (a)	700 kg/m^3 (a)	700 kg/m^3 (a)	700 kg/m^3 (a)	700 kg/m^3 (b)
Silica fume		-	-	80 kg/m^3	80 kg/m^3	80 kg/m^3	80 kg/m^3	80 kg/m^3
GGBS		-	-	320 kg/m^3	320 kg/m^3	320 kg/m^3	320 kg/m^3	320 kg/m^3
Cement		400 kg/m^3	400 kg/m^3	-	-	-	-	-
LC		-	-	40 kg/m^3	40 kg/m^3	40 kg/m^3	40 kg/m^3	40 kg/m^3
LH		-	-	40 kg/m^3	40 kg/m^3	40 kg/m^3	40 kg/m^3	40 kg/m^3
Water		200 L/m^3	-	-	-	-	-	-
Rainwater			200 L/m^3	200 L/m^3	200 L/m^3	200 L/m^3	200 L/m^3	200 L/m^3

8.3. Fresh sustainable concrete properties

Slump and density tests were conducted for all concrete mixes. Table 8.2 illustrates all density and slump readings for the five different mixes. For the rainwater mix (RW) there was no notable changes in density and slump compared to the reference mix, this indicates that rainwater has no significant effect on fresh concrete properties. However, workability decreased by 75% when all of the constituents were added together in one mix, which recovered by 20% when the aggregates were particle packed. The replacement of Portland cement with GGBS did cause an 8% loss in density due to low specific gravity of GGBS compared to Portland cement. On the other hand, with the S2 mixes the density was expected to be less due the chipper rubber aggregate's low density.

Table 8.2 Fresh sustainable concrete properties, RW: rainwater mix S1: sustainable mix 1, S1PP: sustainable mix 1 particle packed, S2: sustainable mix 2, S2PP: sustainable mix 2 particle packed

Mix	Density		Slump	
	Batch 1	Batch 2	Batch 1	Batch 2
Reference mix	2380 kg/m^3	2375 kg/m^3	145 mm	150 mm
RW	2375 kg/m^3	2370 kg/m^3	145 mm	145 mm
S1	2178 kg/m^3	2163 kg/m^3	35 mm	30 mm
S1PP	2290 kg/m^3	2305 kg/m^3	40 mm	45 mm
S2	2003 kg/m^3	2018 kg/m^3	50 mm	55 mm
S2PP	2157 kg/m^3	2182 kg/m^3	55 mm	60 mm
S2”PP	2240 kg/m^3	2265 kg/m^3	60 mm	65 mm

8.4. Sustainable concrete compressive strength

For the concrete compressive strength, Firstly, Table 8.3 and Figure 8.1 illustrate harvested rainwater mix, again there is no change to in the compressive strength. This means that using harvested rainwater as a replacement for normal tap water has no deleterious effect on the compressive strength of concrete.

Table 8.3 Harvested rainwater mix compressive strength

Day	Compressive strength in MPa			
	Reference mix	Average	Rainwater	Average
7	24.5	24	24	24
	21.5		23	
	23.5		24.5	
	25		25	
	25.5		23.5	
28	35.5	34.3	34.5	34
	34		33	
	35		34	
	33		33.5	
	34		35	
56	39	37.8	36	37.3
	38		37.5	
	37		38	
	36.5		36.5	
	38.5		38.5	

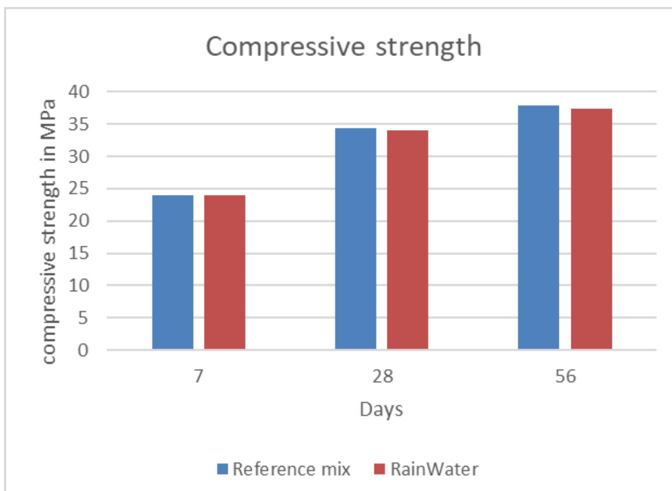


Figure 8.1 Harvested rainwater mix compressive strength

Secondly, S1 and S1PP mixes compressive strengths are displayed in Table 8.4 and Figure 8.2. At no age did the compressive strength surpass the reference mix for the S1 mix as when mixing the different recycled constituents together, had an impact on the strength, manly this could be the effect of adding the recycled sand as it was the weakest constituent as displayed previously in Chapter 6. At 28 days the S1 mix average was around 31.8 MPa, that is lower than the baseline by approximately 6%. Nevertheless, when the same mix was particle packed, in the S1PP the loss of strength was recovered and that was the aim of using the methodology explained in Chapter 4. Not only did the S1PP mix reach baseline reference mix strength at 28 days, but it surpassed the reference mix after 56 days by 8 % at an average of 41 MPa. This is a noteworthy outcome as it supports the main hypothesis in this thesis that it is possible to manufacture 100% recycled concrete using RCA without loss of compressive strength, although it is noted that a mix adjustment to achieve optimum packing was necessary to achieve this.

Table 8.4 Sustainable concrete compressive strength, S1: sustainable mix 1, S1PP: sustainable mix 1 particle packed

Day	Compressive strength in MPa					
	Reference mix	Average	S1	Average	S1PP	Average
7	24.5	24	15	15.8	17	16.8
	21.5		16		18.5	
	23.5		16.5		16.5	
	25		16		16	
	25.5		15.5		16	
28	35.5	34.3	30	31.8	35	34.6
	34		33.5		34.5	
	35		32		36	
	33		31.5		33	
	34		32		34.5	
56	39	37.8	37	36.0	40	41.0
	38		35		42.5	
	37		35.5		41	
	36.5		36.5		40.5	
	38.5		36		41	

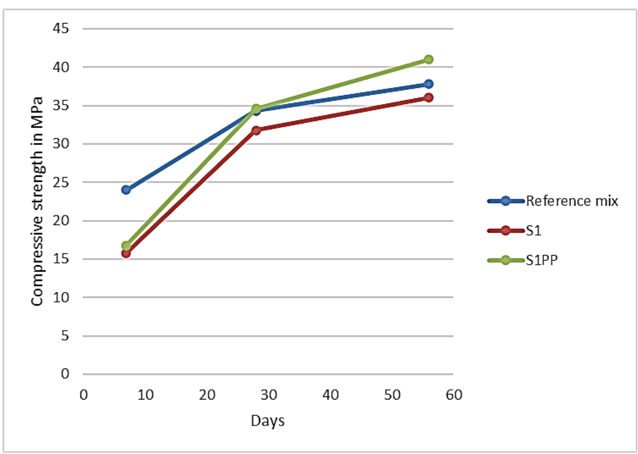


Figure 8.2 Sustainable concrete compressive strength, S1: sustainable mix 1, S1PP: sustainable mix 1 particle packed

Finally, the chipped rubber aggregate based mixes S2, S2PP and S2"PP mixes were also tested for compressive strength, which results are illustrated in Table 8.5.

Table 8.5 Sustainable concrete compressive strength in MPa, S2: sustainable mix 2, S2PP: sustainable mix 2 particle packed and 10% recycled treated sand, S2"PP: sustainable mix 2 particle packed and 20% recycled treated sand

Day	Compressive strength in MPa					
	S2	Average	S2PP	Average	S2"PP	Average
7	10	9.7	16	15.2	17	17.1
	9.5		14		18.5	
	10.5		15.5		16.5	
	9		16		16.5	
	9.5		14.5		17	
28	13.5	13	21.5	20.4	23.5	22.8
	13.5		20		22	
	12.5		21		23.5	
	13		19		22.5	
	12.5		20.5		22.5	
56	15	14.6	24	23.9	25	26.0
	14.5		23.5		27	
	14.5		25		26.5	
	15		23.5		25.5	
	14		23.5		26	

The S2PP mix did not regain full compressive strength that was also due to the replacement of the normal sand with the recycled sand. However, S2"PP uses 20% of silica fume treatment for recycled sand mentioned in Chapter 6, and that helped to regain the loss in compressive strength. S2"PP compressive strength at 28 days increased by 75% from the original chipped rubber mix (Figure 8.3).

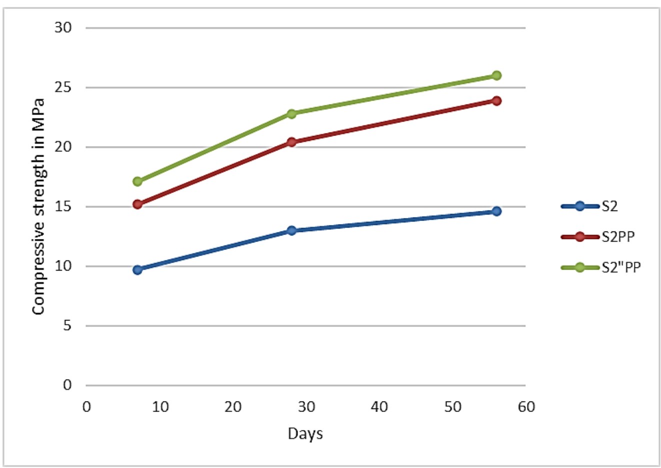


Figure 8.3 Sustainable concrete compressive strength, S2: sustainable mix 2, S2PP: sustainable mix 2 particle packed and 10% recycled treated sand, S2"PP: sustainable mix 2 particle packed and 20% recycled treated sand

Although the strength of all rubber-based mixes did not surpass the reference concrete mix, yet, it can still be used as a structural material with an average compressive strength of 22 MPa at 28 days. Also, comparing this with the untreated rubber mix at the beginning of chapter 3, S2”PP increased by more than 600%, which was a key aim of this thesis.

8.5. Sustainable concrete elastic modulus

Elastic modulus results are illustrated in Table 8.6. The sustainable concrete combined mix S1 E value was lower than the reference mix by about 5%. The GGBS/silica fume binder is compensating for any loss in the elastic modulus. Furthermore, the elastic modulus results for the S1PP are greater than the S1 results by an 8% and that is due to the effect of aggregate particle packing. On the other hand, 28 days result for the chipped rubber sustainable mix had a lower elastic modulus than the reference mix by about 25%, yet that was expected from chipped rubber concrete due to its very low modulus value. However, with aggregate particle packing chipped rubber concrete modulus of elasticity did increase by 10%, but still some 25% less than the baseline reference mix value.

Table 8.6 Sustainable concrete elastic modulus S2: sustainable mix 2, S2PP: sustainable mix 2 particle packed and 10% recycled treated sand, S2”PP: sustainable mix 2 particle packed and 20% recycled treated sand

Mix	7 days	28 days	56 days
Reference mix	23.1 GPa	28.0 GPa	29.3 GPa
RW	23.0 GPa	28.4 GPa	29.0 GPa
S1	22.4 GPa	27.1 GPa	28.3 GPa
S1PP	25.0 GPa	28.8 GPa	29 GPa
S2	17.4 GPa	18.9 GPa	19.0 GPa
S2PP	18.1 GPa	19.8 GPa	20.0 GPa
S2”PP	18.1 GPa	20.9 GPa	21.0 GPa

8.6. Conclusions

The combination of the different recycled and by-product constituents in one sustainable concrete mix was only achieved by examining and treating each constituent separately first. The conclusions from this chapter, the culmination of the various research strands in this thesis, are as follows:

- The harvested rainwater had no effect on the mechanical properties of concrete.

- On the other hand, particle packing theory enhanced the compressive strength of the S1PP by 8 % after 56 days it also increased the elastic modulus of a concrete by 8% after 28 days.
- Achieving this means that concrete can be formed by substituting 100% of its constituents, with recycled concrete aggregate, waste, and by-product materials, without affecting its compressive strength and elastic modulus, which was a key objective of this thesis
- When 10% treated ,recycled sand was added to the treated chipped rubber concrete mix it decreased the chipped rubber concrete mix compressive strength, although that loss of strength which was compensated for by using the 20% SF treated recycled sand.
- Chipped rubber aggregate mixes compressive strength increased by over 600% from the original mix at Chapter 3. But it failed to match the baseline reference mix strength. Reaching an average of 25 MPa after 56 days due to the GGBS cement is a clear indication that rubber-based mixes can be used for low strength structural components.

Chapter 9

Conclusions and recommendations

9. Conclusions and recommendations

This study aimed to use solely recycled materials as constituents to form a novel concrete without adversely affecting its key mechanical properties: workability, density, strength and elastic modulus. This will require pre-treatment of some constituents before using them to compensate for the natural strength loss arising from their addition.

This aim was fulfilled because it confirmed the hypothesis that concrete can be formed by substituting 100% of its constituents with recycled, waste and by-product materials, without affecting its strength, elastic modulus, workability, and density through proposed novel pre-treatment methods, processes, and recycled activators.

9.1. Chipped rubber

Concrete's mechanical properties are massively affected by the usage of rubber as an 100% replacement in a chipped rubber concrete mix. When batching to replace normal aggregates with a 100% chipped rubber aggregate, a given weight of the aggregates will produce a greater volume, so batching of chipped rubber aggregate should only be by volume. The lighter weight of chipped rubber concrete is the principal reason for the decrease in workability, in addition to other characteristics of chipped rubber such as lower surface bond, water repellence and surface friction. Ultraviolet treatment affects the surface of the rubber, causing a stiffer surface with less friction and small cracks on the surface to improve the bond with cement paste. However, the core of the chipped rubber is still elastic. On the other hand, sulphuric acid treatment significantly enhances the chipped rubber stiffness, and it also contributes to eliminating their angularity, making their surfaces smoother than the ones treated with ultraviolet light. Both ultraviolet and H_2SO_4 treatments positively impacted the behaviour of the chipped rubber aggregates in the concrete matrix and partly helped in restoring the original concrete workability. Ultraviolet light chipped rubber treatment increased the strength of concrete by 10%. However, sulfuric acid treatment had a significant effect in increasing the strength of concrete by 143%, principally due to stiffening of the aggregate. Modulus of elasticity also improved significantly when chipped rubber was treated with H_2SO_4. Adding 6 mm limestone as a partial replacement of the sulfuric acid treated chipped rubber mix increased the strength more and decreased the workability due to the larger surface area of the 6 mm aggregates. Despite the increased weight particle packing chipped rubber with the 6 mm by-product aggregate increases the compressive strength by about 650 % and the elastic modulus by 980%.

9.2. Recycled aggregates

Recycled concrete aggregates contain additional pores on the adhered mortar and will cause a drop-in workability, strength, and elastic modulus of the concrete. Therefore, recycled concrete aggregates need to be:

- separated out and added to the new mix based on strength
- washed clean of dust that may otherwise affect the bounding of the aggregates
- dried so that the surface pores are air filled
- coated with silica fume slurry using just enough to cover the available surfaces
- left for 28 days to set and harden

Pre-treating recycled aggregates with micro silica improves the workability and strength of the concrete. This is due to the reduction in the recycled aggregate's porosity after treatment because of the micro silica very fine particles that can fill the surface capillary pores of the recycled concrete aggregates. Note that micro silica is prepared separately with a 0.80 ratio of water to micro silica, prior to mixing with the recycled aggregates and only is added as a slurry. This pre-treatment method has an approximate 7% effect in increasing the concrete strength in both treated types.

Further, full drying the recycled concrete aggregates before treating them with silica fume increased the strength by about 45% due to the fact all capillary pores and surface of the aggregates are only filled with silica fume paste and not residual saturated water. Furthermore, when recycled concrete aggregates was dried treated and particle packed the strength increased by about 50%. However, that can cause a drop-in workability which can be mitigated by leaving the treated aggregates to dry for 28 days to make sure that all of the silica fume coating had set. On the other hand, treating fine recycled concrete aggregate (recycled sand) with micro silica fume regains part of the concrete's workability. There was difference between the RSF10 and RSF20 in terms of compressive strength and that is due to the extra amount of silica fume in the treatment phase. Even though, at 28 days treated recycled sand with 10% SF recycled is lower than the reference mix by about 5%, yet this decrease in strength was compensated for when recycled sand was used with recycled concrete aggregates. The research recommends that the addition of silica fume is to be made by the saturated surface dried sand.

9.3. Ground granulated blast furnace slag

Replacing 100% of Portland cement with GGBS and silica fume drastically decreases the concrete strength, therefore the use an alkaline activator to activate the GGBS and silica fume is needed. The novelty is that lithium chloride and lithium hydroxide worked very effectively as recycled alkaline activators for the GGBS and silica fume cementitious mixture. Both lithium chloride and lithium hydroxide can be obtained from recycling old lithium batteries which make them both recycled products. Alkaline activators are to be prepared 24h before the mixing even though, it is expected that the reaction of GGBS will not be as fast as the normal Portland cement. However, with these alkaline activators the strength at the 28 day is consistently very similar to that of normal concrete. There was a 500% increase in the 28 days strength when 5% recycled activators were added compared to the equivalent non-activated mix. Moreover, this increased to 900 % when 20% of the recycled activators were used.

This work confirms that Silica fume is to be added as paste and never as a powder as that will course a massive drop in workability.

9.4. Particle packing

The effect of particle packing on the compressive strength of concrete was significant. The void ratio diagram is a noteworthy technique to display the relation between two different aggregates, especially when using recycled aggregates that are irregular in shape and size. The particle packing diagram can illustrate the best packing ratio proportions for the materials. The greater the mean size difference between adjacent materials the lower the void ratio that is detected even with the consideration of the wall effect of the larger sized aggregates on the small ones.

9.5. Combination

The combination of all recycled and by-products after the pre-treatment methods and with the utilisation of particle packing of the aggregates to come up with a novel sustainable concrete mix was only achieved by examining, treating, and testing each constituent separately to identify and overcome its weakness and then to bring the constituents together in to one mix. Achieving this means that concrete can be formed by substituting 100% of its constituents, with recycled, waste and by-product materials, without affecting its compressive strength and elastic modulus. And that is the objective of this thesis.

9.6. Objectives met

- This study aimed to use solely recycled materials as constituents to form a novel concrete without adversely affecting its key mechanical properties specifically (strength, elastic modulus, workability, and density). This objective is successfully accomplished
- This required a pre-treatment of some constituents before using them to compensate for the natural strength loss arising from their addition. This study involved mitigating the negative impact of using these recycled materials individually and collectively:
    - Recycled tyres in the form of chipped rubber, by treating them with sulfuric acid and particle packing them with the 6.3 mm waste aggregates from quarries.

- Recycled concrete aggregate (RCA) from demolished buildings, by drying them then coating them with SF slurry, then drying before using them in a concrete mix.
- Ground granulated blast-furnace slag (GGBS) from the steel manufacturing industry, and silica fume (SF) by activating it with recycled activators lithium chloride and lithium hydroxide recycled from old batteries.

This will also reduce dependence on less sustainable materials, such as quarried aggregates, Portland cement (PC) and normal tap water. The sustainable novel concrete matched the original concretes mechanical properties (such as strength, elastic modulus, density, and workability) in the RCA base mixes. Despite not matching the original concrete strength in the rubber-based mix, yet an increase in compressive strength by about 650 % and the elastic module by 980% from the baseline 100% replaced non-treated rubber mix was achieved.

9.7. Further research

During the experimental work on this thesis, many factors outside the scope of this thesis came to light as being worthy of further research. The key ones of these include the following:

- For future studies on particle packing, one could apply particle packing on cementitious material as well as aggregates, however, by doing this, all of the concrete constituents' amounts would change, and this change needs to be examined and investigated. Moreover, the effect of this change on the concrete's mechanical properties should be investigated.
- Chipped rubber concrete failure type characteristics suggest that chipped rubber concrete is suitable to be use in road barriers and pedestrian pavements as parts of concrete will not shatter because of impact. Also, this suggests investigating the possibility of using this type of concrete in blast resistant concrete buildings.
- Examine the ability to obtained sulfuric acid from fossil fuels burning activities in some factors, where the smoke from that process contains sulphur dioxide. And sulphur dioxide

gas changes into sulfuric acid when it encounters water so this could be researched as recycling emitted gas to sulfuric acid could be used in treating chipped rubber aggregates.

- This research did not focus on the economic and carbon cost reductions, so further research could address this for by-products, treatment methods and/or recycling.

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