University of Southern Queensland

Faculty of Health, Engineering and Sciences

Investigation into the flexural characteristics of cold formed steel filled with rubberised concrete

A dissertation submitted by

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ABSTRACT

Worldwide environmental concerns regarding large stockpiles of waste tyres have led to investigations into alternate options for the disposal of waste tyres. One possibility to decrease the environmental burden created by waste tyres is for the building and construction industry to incorporate recycled rubber into concrete.

There are various issues that occur when introducing recycled rubber into concrete which have been identified in prior investigations. The main issues identified include the difficulty of making a homogeneous concrete mixture with rubber and the loss of compressive and flexural strength with higher rubber volumes. This dissertation investigates these issues and provides a thorough insight into crumb rubber concrete (CRC) and its characteristics.

Many previous investigations have introduced various treatment methods in order to improve the compressive strength of CRC. An already established method of rubber treatment using sodium hydroxide (NaOH) has been adopted in this investigation. NaOH treatment is considered the best and most widely used treatment method for rubber particles and will serve as a good comparison for other treatment methods investigated in this study.

In addition to NaOH treatment, a relatively new method of water treatment has been investigated. This method involves soaking rubber particles in water for a set period of time. A number of fresh and hardened concrete tests were performed using the new treatment method with varying contents of crumb rubber.

The effectiveness of both treatment methods listed in this investigation has been determined by comparing the strength characteristics of treated rubber concrete with untreated rubber concrete.

Within this study it was discovered that NaOH treated samples displayed 16% higher compressive strength when compared with untreated rubber samples. Water soaked treated samples displayed 26% higher compressive strength when compared with untreated rubber samples.

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I certify that the ideas, designs and experimental work, results, analyses and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

Brendon Heath

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CHAPTER 1

1.0 INTRODUCTION

1.1 Research Scope

The growing stockpiles of waste tyres are a problem that is faced by many countries around the world. Environmental concerns have been raised due to the length of time taken for rubber to break down. Hyder (cited in Australia Department of Environment 2015, p.22) reported that approximately 51 million tyres were disposed of between 2013 and 2014 in Australia. Only 3% of recycled tyres are used in construction applications in Australia, where as in other regions of the world such as Europe and North America significantly larger amounts like 14% and 9% respectively are being recycled (Oikonomou & Mavridou 2012).

The demand for raw materials has increased rapidly in recent years. Crumb rubber could potentially provide some relief by utilising recycled tyre which would reduce the impact on the dwindling natural gravel and sand deposits.

Since the 1990's many investigations have been done to determine if recycled tyres are a variable option for use in the construction industry (Eldin & Senouci 1994; Toutanji 1996). The amount of tyres going to landfill could be drastically reduced by using recycled tyres as a substitute material in the construction industry which would decrease the strain on the environment and natural resources.

Traditional concrete has low ductility and tensile strength (Khorrami et al. 2010). Toutanji (1996); Kaloush et al. (2005) have shown that the inclusion of crumb rubber as a partial replacement of the mineral aggregate in concrete can improve ductility and tensile strength. One drawback to crumb rubber concrete (CRC) however is its lower compressive strength (Toutanji 1996; Kaloush et al. 2005; Bewick et al. 2010; Ling et al. 2009). Investigations of CRC undertaken by Youssf et al. (2014) reported losses of up to 40% of the compressive strength for specimens containing high rubber percentages. The fact that CRC has low compressive strength makes it an undesirable product for structural applications (Aiello & Leuzzi 2010).

There has been large development of permanent formwork systems in recent years. This has created the opportunity to use rubberised concrete in structural applications. The permanent formwork provides significant strength to the slab. This enables the use of CRC as the topping material.

A thorough investigation into the optimal crumb rubber content is required to determine the design mix that exhibits the best strength characteristics in relation to rubber content. The main focus in this research will be on increasing the environmental advantages of CRC while decreasing the strength disadvantages of CRC.

A variety of treatments are available to help neutralize the negative effect of rubber in concrete. Therefore, treatment techniques of rubber will be discussed in this research. Two different treatment methods of crumb rubber will be examined. The results of concrete with treated rubber will be compared to the results of concrete without treated rubber. The research will focus on commonly used NaOH and a relatively new method of water soaking. After assessing the two rubber treatments, only one method will be selected for additional testing. The selected treatment will take into account industrial friendliness of the method as well as strength characteristics.

As suggested in literature the size of rubber particles affect the properties of rubberised concrete (Sukontasukkul & Tiamlom 2012). For this study, the particle size for crumb rubber will be limited to 0.7mm to minimise the negative effect of adding rubber into concrete. Furthermore, according to Youssf et al. (2014) the maximum percentage of fine aggregate replaced by crumb rubber should be limited to 20%. Anything more than 20% yields extremely low compressive strengths unsuitable for structural applications.
This research will examine the replacement of fine aggregate with crumb rubber for the best strength characteristics. The optimal mix will be determined by comparing the characteristics of the CRC specimens with the control mix specimens without crumb rubber.

This research is of great importance for future sustainable construction practices because concrete is one of the most extensively used building materials in the construction industry around the world.

1.2 Research objectives and Significance

1.2.1 Objectives

Considerable research has been conducted on the idea of using crumb rubber in concrete. However, only very few investigations have been performed on the various treatment methods for rubber. All types and sizes of recycled rubber are grouped under the general term of rubberised concrete. The objective of this research is to extend the knowledge of CRC treatment methods. In this study, the testing will not only assess the mechanical properties of CRC, but will also investigate rubber treatment methods. The major objectives of this research are as follows:

• Examining the past and existing studies of rubberised concrete gather and apply relevant information.

• Optimising a pre-determined CRC design mix by modifying certain constituents and rubber treatment methods to achieve desirable characteristics for use in permanent formwork.

• Measuring the common mechanical characteristics of CRC through laboratory testing. The potential advantages and disadvantage of incorporating different volumes of crumb rubber into the concrete will be assessed.

• Investigating the advantages and disadvantages of treated rubber in CRC with the inclusion of NaOH treatment and a relatively new treatment method of water soaking.

• Establishing a relationship between the strength characteristics of CRC and various rubber treatments and rubber contents.

1.2.2 Significance

The problem of waste rubber and the damage to the environment is immense and getting worse. Therefore research into innovative ways of utilising recycled crumb rubber in more environmentally friendly applications is required to continue.

The production of rubberised concrete has been linked to many complications in previous research. This study is aiming to provide a clear understanding on the effects of using scrap tires as an aggregate in concrete.

Effective utilisation of waste rubber is essential for the preservation of the environment. Many unfavourable and unsafe conditions are created from the large stockpile of used automotive rubber tyres. Using recycled rubber in concrete is one possible way of reducing the damage imposed by automotive tyre waste.

It is anticipated that this research will benefit the construction industry by providing additional data for the construction of residential slabs. Furthermore, the conclusions found in this research could possibly contribute to the formation of concrete specifications for CRC in Australian residential slabs.

CHAPTER 2

2.0 LITERATURE REVIEW

2.1 Introduction

A large number of investigations have been conducted in order to determine the effects of adding recycled rubber to concrete. Although the literature addresses a wide variety of matters, this review will place emphasis on three main subjects which appear frequently throughout the literature. These issues include: data relating to recycled rubber for use in CRC, the fresh and hardened characteristics of CRC and rubber treatment methods. These subjects are presented in a diverse range of contexts in the literature. The primary focus in this study will be the application to Portland cement CRC.

2.2 Recycled Rubber

The role rubber particles play in a concrete mix will be critically reviewed in this study. Furthermore, the effects of various rubber sizes on the characteristics of concrete will be clarified. Desirable characteristics such as better ductility and lower density are some of the beneficial characteristics that can be attained with the inclusion of recycled rubber into concrete mix (Khatib & Bayomy 1999; Khaloo et al. 2008). Better sound insulation and fire resistance for CRC was reported making it an ideal selection for residential slab applications (Bewick et al. 2010; Sukontasukkul 2009; Rangaraju et al. 2012).

Numerous investigations into the compressive strength of CRC have observed reduced compressive strength which restricts its use in most applications (Khatib & Bayomy 1999; Bewick et al. 2010; Ling et al. 2009; Khaloo et al. 2008). The cause of the reduced compressive strength is primarily due to the elastic properties of rubber in the concrete mixture. Incorporating recycled rubber into the concrete mixture alters its mechanical properties. The change from a brittle to ductile material is a particularly noticeable feature when dealing with higher volumes of rubber (Eldin & Senouci 1994). Replacing fine or coarse aggregates in concrete mixes with recycled rubber has been attempted numerous times. The size, type and content of rubber added to concrete are all known to significantly affect the characteristics of concrete. Furthermore, various techniques of pre-treating recycled rubber prior to mixing in concrete were found to considerably affect strength characteristics (Khaloo et al. 2008; Youseff et al. 2014).

The most critical factor when examining recycled rubber is the particle size (Taha et al. 2009). The three size classifications for recycled rubber are as follows:

Chip rubber: Used to replace coarse aggregate with a dimension of 4.75mm or larger (Taha et al. 2009).

Crumb rubber: Used to replace fine aggregate with a dimension between 4.75mm and 0.075mm (Li et al. 1998; Kaloush et al. 2005).

Ash rubber: Used as a filler in concrete with a dimension of less than 0.075mm (Al-Akhras & Smadi 2004).

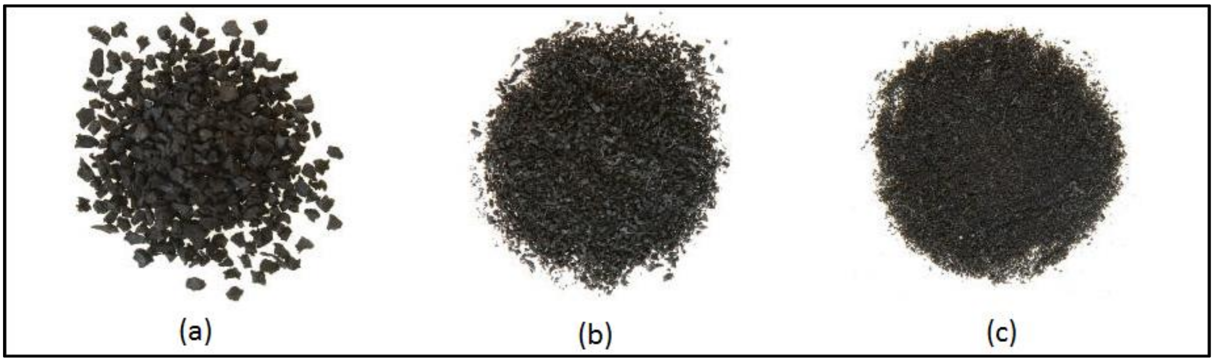

Figure 1: The three main types of recycled rubber used in CRC, (a) chip rubber, (b) crumb rubber and (c) ash rubber (ReRubber 2016).

The specific gravity (SG) for each size of recycled rubber differs as shown in table 1. Various explanations have been made for the deviation in SG. Fattuhi & Clark (1996) theorised it could potentially be the differing sources of rubber. Alternative explanations relate to the manufacturing process and the ability to remove steel wire from the rubber particles. More steel content would increase the SG value. The SG of the recycled rubber can make mixing and compaction of CRC challenging, possibly resulting in segregation of aggregates (Mohammadi 2014).

Table 1: Properties of recycled rubber used in CRC (Taha et al. 2009; Li et al. 1998; Kaloush et al. 2005; Al-Akhras & Smadi 2004).

Rubber types	Average size (mm)	Specific gravity
Ash rubber	<0.075	0.90-2.25
Crumb rubber	0.075 to 4.75	0.55-1.25
Chip rubber	>4.75	1.10-1.15

This research will consider crumb rubber with dimensions between 2.5mm and 0.075mm. The recycled rubber that will be used is comprised of various sources of rubber manufactured by Tyrecycle.

2.3 Physical and Mechanical properties of Crumb Rubber Concrete

2.3.1 Fresh characteristics of Crumb Rubber Concrete

Concrete is simply the mixture of aggregates, cement and water. In recent times, the use of many additives like silica fume, fly ash, superplasticiser, accelerating or retarding agents have been used to improve the fresh and hardened characteristics of concrete. Crumb rubber is another material that is used primarily as an aggregate replacement.

The two main characteristic features of fresh CRC that will be focused on in this research are workability and density. Reductions in slump and density have been observed in CRC (Fattuhi and Clark 1996, Batayneh et al. 2008 and Aiello et al. 2010). For a mix design, material properties such as density and particle size distribution need to be identified prior to mixing and is required to satisfy consistency and workability requirements.

Mixing procedures, compaction techniques and climatic conditions all impact on the properties of fresh concrete. The Australian Standards will be applied for the creation of standard test specimens for all procedures and techniques applied in this study.

Literature indicated that characteristics of a fresh concrete mixture changed when using recycled rubber in a concrete mix. Fresh characteristics of concrete have been investigated thoroughly when various rubber contents were added to a concrete mixture. Details are discussed in the following sections.

Workability

Concrete in its fresh state is characterised by two main features. It should be in a plastic or semifluid state and have enough workability to be moulded by hand without difficulty (Mehta et al. 2006).

Workability is a crucial characteristic of fresh concrete. A very wet concrete mix may be easier for casting, however if it does not exhibit enough cohesion it may be considered unsatisfactory and segregate much more easily (Mehta et al. 2006).

It has been observed that rubber particles segregate far more easily than standard concrete aggregates during mixing, casting and compacting. This is primarily due to the difference in unit weight between rubber and other concrete constituents (Najim & Hall 2010). Therefore attention must be given when adding crumb rubber particles into a concrete mixture to avoid segregation.

Workability is also described as the ability of a concrete mix to resist segregation. Ideally, concrete constituents should bind well and avoid separating during transport and handling. The factors influencing segregation of aggregate can be controlled by carefully modifying the water content, admixtures and the particle distribution of aggregates.

Various testing methods are available to measure the workability of concrete in its fresh state. Only visual inspections and slump values will be considered in this study. Visual inspections evaluate whether the CRC mixture is homogenous, while the purpose of the slump test is to determine the consistency of fresh concrete and to check the workability of the mixture.

The literature shows that the inclusion of rubber into concrete mixtures reduces its workability and shows a strong correlation between reduced slump values and the addition of rubber (Rangaraju et al. 2012; Khaloo et al. 2008, Mavroulidou & Figueiredo 2010). To what extent the slump values are reduced is yet to be determined.

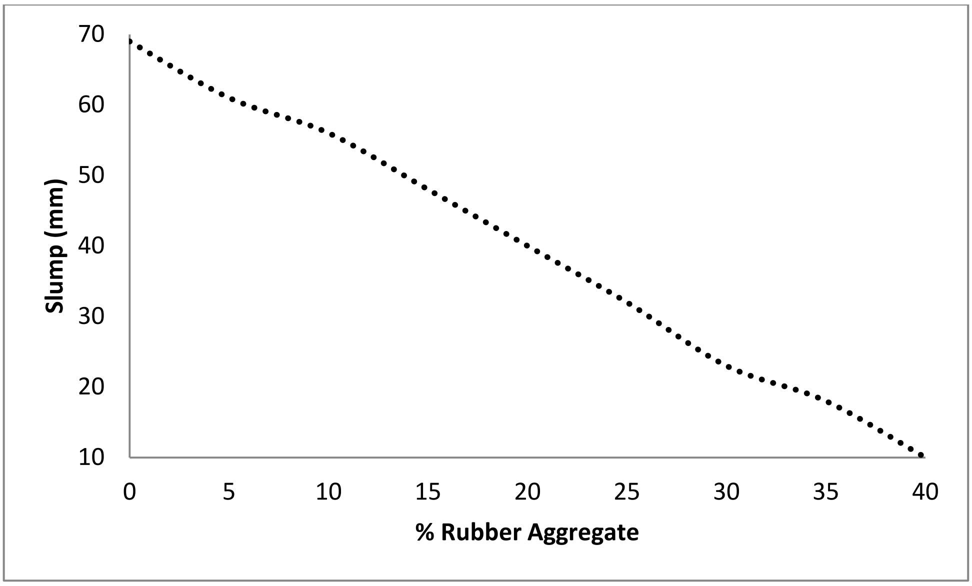

Figure 2: Effect of rubber content on the slump value (Mavroulidou & Figueiredo 2010)

Cairns et al. (2004) found CRC tended to have a reduction in slump of 85% when compared to ordinary concrete. Investigations conducted by khatib and Bayomy (1999) achieved similar results when partially replacing the fine aggregate with crumb rubber.

Superplasticiser will be used to achieve good workability of the CRC mixture. Testing conducted by Mohammadi (2014) is one example where desired workability was influenced by altering the volume of superplasticiser.

Density

Recycled crumb rubber is a lightweight aggregate replacement. Consequently, when introduced to the concrete mixture a reduction of density can be observed (Emira & Bajaba 2012). Literature has established that introducing rubber into a concrete mixture to replace aggregates will result in a reduction of density (Siddique et al. 2008; Youssf et al. 2014).

Fattuhi & Clark (1996) found this is primarily due to the much lower density of recycled rubber compared to ordinary concrete constituents.

When substituting fine aggregates for crumb rubber at 5% to 20% of total volume of fine aggregates, a reduction of 14% to 28% was observed depending on the rubber content and rubber type used (Sukontasukkul 2009; Rangaraju et al. 2012). A proportionate reduction in strength of 6% to 15% was recognized by Zheng et al. (2008) when substituting fine aggregates for crumb rubber at values of 8% to 24% of total volume of fine aggregates.
A number of detailed studies have been conducted to determine the effect of rubber content on CRC density. Investigations conducted by Khatib & Bayomy (1999); Khaloo et al. (2008) found that the key factor effecting the reduction of CRC is rubber content. Furthermore, Kaloush et al. (2005) found a reduction of 100kg/m3 for every 25kg of rubber added to a concrete mixture.

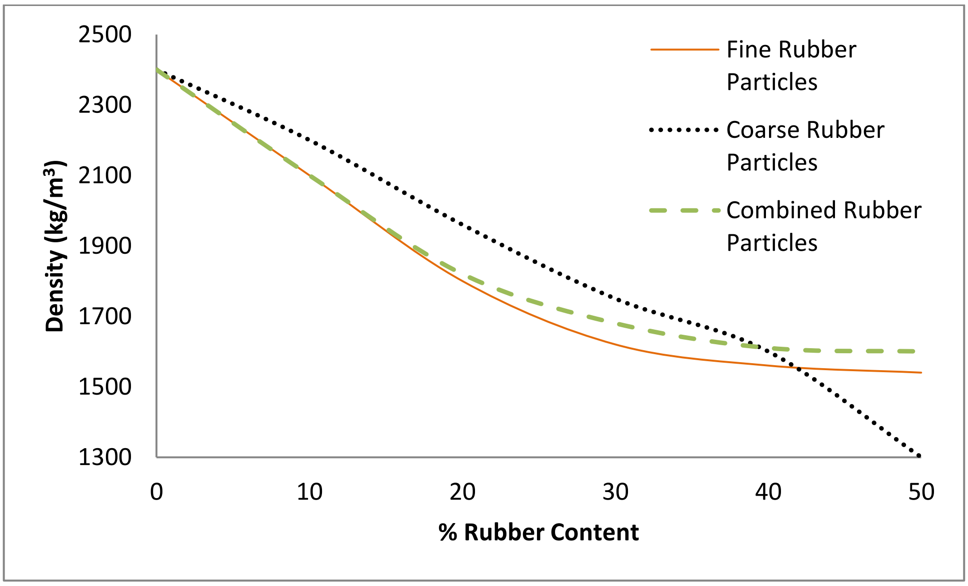

Figure 3: Effect of rubber content and rubber particle size on density (Khaloo et al. 2008)

Other factors such as water to cement ratio and rubber particle size were noted as having no substantial impact on density of rubberised concrete mixtures (Emira & Bajaba 2012; Khatib & Bayomy 1999).

2.3.2 Hardened characteristics of Crumb Rubber Concrete

The hardened characteristics of CRC are heavily reliant on the materials used to make the concrete mixture, as well as the mixing process. The major conclusion drawn from several experimental investigations is the reduction of strength (Tian et al. 2011; Zheng et al. 2008; Kaloush et al. 2005).

The inclusion of recycled rubber particles to a concrete mixture changes many features of hardened CRC. Many of these features have been well documented in great detail in the literature and will be discussed further in the following sections.

Compressive strength

Compressive strength tests are recognized as the most convenient method of determining the properties of hardened concrete. An investigation into rubberised concrete performed by Toutanji (1996) found a reduction in compressive strength when replacing natural aggregates with rubber chips and crumb rubber. When replacing 5%, 10% and 15% of total fine aggregate by volume Khatib and Bayomy (1999) reported losses of 26%, 37% and 42% respectively when compared to ordinary concrete. Other investigations performed by Tian et al. (2011); Zheng et al. (2008) confirmed a similar loss of compressive strength when using recycled rubber in concrete mixtures.

Kaloush et al. (2004) recorded comparable compressive strength losses for CRC for increasing rubber contents; however entrapped air was identified as playing a role in the strength reduction. Additional research determined that the drop in strength from entrapped air could be alleviated with the use of a de-airing agent prior to casting (Kaloush et al. 2004). Experimental testing conducted by Mohammadi (2014) reported that the presence of air in a CRC mixture could be reduced with a technique that involves water soaking particles prior to mixing.

Compressive strength is considered the most significant feature of concrete in the construction industry and is used to specify overall concrete strength. Even though slabs in residential buildings are primarily subjected to tensile stress, compressive strength tests are still the most common test used to determine strength.

An increased reduction of CRC strength when a greater volume of recycled rubber was used has been shown in the literature. For this reason, Khatib & Bayomy (1999) recommend the rubber content used in CRC should not exceed 20% of the total natural aggregate volume in order to mitigate undesirable strength characteristics.

Figure 4 shows a strong correlation between the increase of recycled rubber and the reduction in concrete compressive strength at 28 days.

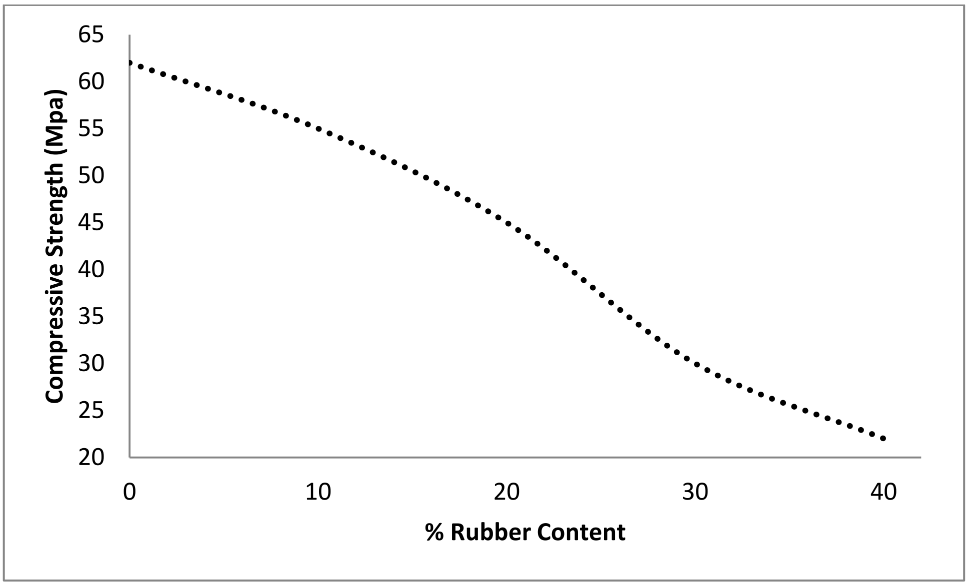

Figure 4: Effect of rubber content and particle size on the compressive strength (Mohammadi 2014)

There are many different explanations for the lower compressive strength in CRC which will be highlighted in the following:

• Richardson et al. (2011); Youssf et al. (2014); Taha et al. (2009) all reported rubber particles having a hydrophobic nature when mixed with water. Small air bubbles attach to the rubber which then gets stirred into the concrete mixture due to the rubber particles ability to repel water. A clear association has been found between the quantity of rubber added to a concrete mix and the air content (Khaloo et al. 2008; Siddique & Naik 2004). It has also been observed that a reduction in concrete strength is commonly caused by an increase in air content (Mehta et al. 2006).

• Youssf et al. (2014) reported reductions in the compressive strength of CRC when using well graded crumb rubber in the concrete mixture. The SG of concrete constituents is much higher than rubber. For this reason, it is possible for rubber particles in a CRC mixture to move up towards the surface if over compaction takes place (Ganjian et al. 2009).

• Rubber particles do not have the ability to carry the load in concrete mixtures as well as concrete aggregates. This is primarily due to the difference of elastic modulus between rubber and concrete aggregates (Youssf et al. 2014). Furthermore, the high levels of deformation in rubber particles in a concrete mixture when loads are applied leads to premature failure.

• Poor bonding between recycled rubber particles and Portland cement paste is caused by the presence of zinc stearate. Zinc stearate creates a film over the rubber resulting in poor cohesion between rubber and cement paste and ultimately poor compressive strength (Yousff et al. 2014). Rubber pre-treatment has been found to not only remove the zinc stearate from the rubber but also create a rougher surface texture which provides greater cohesion (Mohammadi 2014).

Flexural Strength

Flexural strength testing of CRC has shown very similar results to the compressive strength testing. Mixtures with aggregates partially replaced by recycled rubber were found to have flexural strengths lower than concrete made with conventional aggregates (Kaloush et al. 2004; Ganjian et al. 2009).

Investigations performed by Ganjian et al. (2009) found that the flexural strength of concrete decreased as the amount of recycled rubber increased in a mixture. Ganjian et al. (2009) reported flexural strength losses of approximately 25% for a 10% replacement of fine aggregate volume.

However, other investigations performed by Benazouk et al (2007); Holmes et al. (2014) reported increases in flexural strength with optimal rubber contents between 20% and 30%. It is theorised that the rubber particles absorb more plastic energy therefore reducing flexural failure (Holmes et al. 2014). Therefore, more research is required in this area.

Modulus of elasticity

Several investigations into CRC have found increasing the content of rubber in a concrete mixture reduces its modulus of elasticity (Zheng et al. 2008). Standard concrete aggregates generally have an elastic modulus of 50 GPa while crumb rubber is approximately 0.001 to 0.01 GPa. This results in CRC having a lower elastic modulus than standard concrete (Khaloo et al. 2008; Kaloush et al. 2005; Zheng et al. 2008; Turatsinze & Garros 2008).

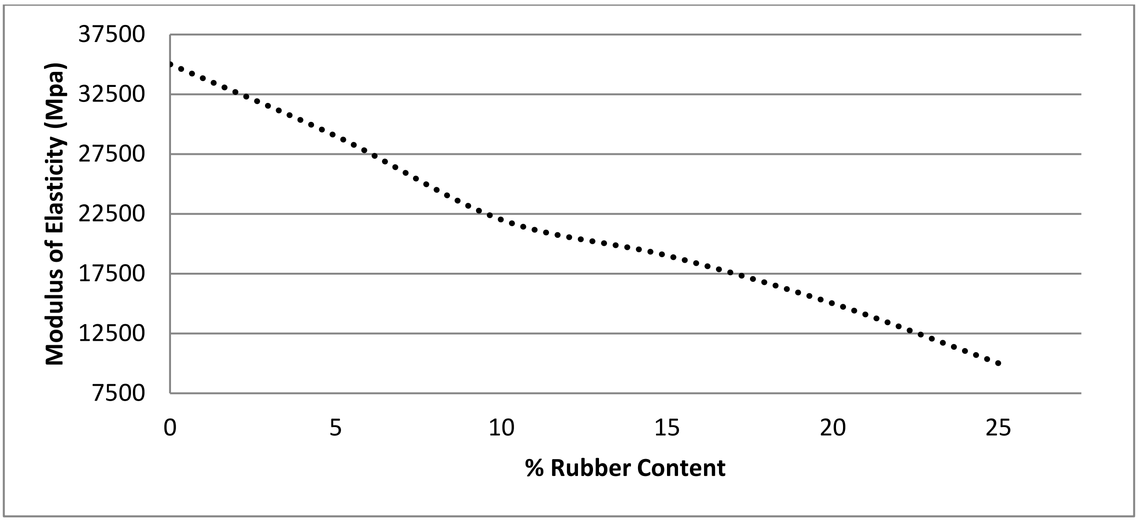

Figure 5: Effect of crumb rubber on the modulus of elasticity (Turatsinze & Garros 2008)

When replacing aggregate with rubber content up to 20%, Youssf et al. (2014) reported a loss of 30% for the modulus of elasticity. It is well established in the literature that the reduction of the modulus of elasticity for CRC is greatly influenced by the proportions of concrete constituents (Ho et al. 2012; Ganjian et al. 2009). Additionally, the rubber particle size has little influence on the modulus of elasticity (Zheng et al. 2008).

2.4 Rubber Treatment Methods

Issues regarding reduced compressive strength and lack of uniformity have been identified when introducing rubber into concrete mixtures (John & Kardos 2011; Ho et al. 2012; Turatsinze & Garros 2008). These issues are the product of major differences between the properties of rubber particles and concrete aggregates.

Rubber particles have an approximate SG of 1 while cement paste and concrete aggregates have a SG of 2.2 and 2.6 respectively. Consequently making a uniform and homogeneous

CRC mixture can be difficult. Furthermore, rubber particles introduce large volumes of air into a concrete mixture which further contributes to reduced compressive strength (Kaloush et al. 2005).

Several researchers also reported poor bonding between rubber particles and cement paste as being an additional reason for reduced compressive strength (Khorrami et al. 2010; Turatsinze et al. 2006; Pacheco-Torgal et al. 2012). This has resulted in investigations into the improvement of bond between rubber and cement paste (Ho et al. 2009; Segre et al. 2000; Zheng et al. 2008). These methods are costly with inconclusive results being obtained.

Numerous investigations have been conducted on CRC, however most take no special consideration when introducing rubber into the concrete mixture and introduce rubber particles using the same method as any concrete aggregate.

For this investigation both surface modification treatment with NaOH and a water soaking treatment will be reviewed and discussed in the following sections.

2.4.1 Sodium Hydroxide (NaOH)

One common method of rubber treatment involves soaking the rubber particles in a chemical solution before adding them to the concrete mixture. Chemical treatment of rubber serves two purposes. They clean any impurities off the surface of the rubber such as oil, dust and dirt and they give the rubber a rougher surface finish (Balaha et al. 2007). A number of alkaline and acidic solutions have been used to achieve this (Tian et al. 2011). Sodium hydroxide (NaOH) is the most commonly used treatment technique for improving the bond between cement paste and rubber particles (Youssf et al. 2014; Siddique & Naik 2004).

Investigations performed by (Balaha et al. 2007; Pelisser et al. 2011; Youssf et al. 2014) found that the NaOH treatment was effective and the strength of concrete improved greatly. However, other investigations found that the NaOH treatment method negatively influenced the strength of CRC (Khorrami et al. 2010; Tian et al.2011). Khorrami et al. (2010) found that the negative influence on concrete strength could be explained by pores on the surfaces of the rubber particles that are caused by the NaOH treatment method. The pores entrap air bubbles which then finally get introduced to the concrete mixture which would lead to a reduction in compressive strength (Khorrami et al. 2010).

Various durations to perform the NaOH treatment method have been conducted by various investigators. Studies conducted by Segre & Joekes (2000); Khorrami et al. (2010); Balaha et al. (2007) show a treatment of rubber for between 5 to 30 minutes while others treated the rubber for as long as 24 hours (Tian et al. 2011). For this experimental study duration of 30 minutes has been selected. A treatment process that minimises time and costs will be easier to implement in industry and therefore is of primary importance.

2.4.2 Water soaking

Investigations performed by Mohammadi et al. (2014) found that when introducing rubber directly into a concrete mixture, air bubbles attach to the rubber particles which are then introduced into the concrete mixture.

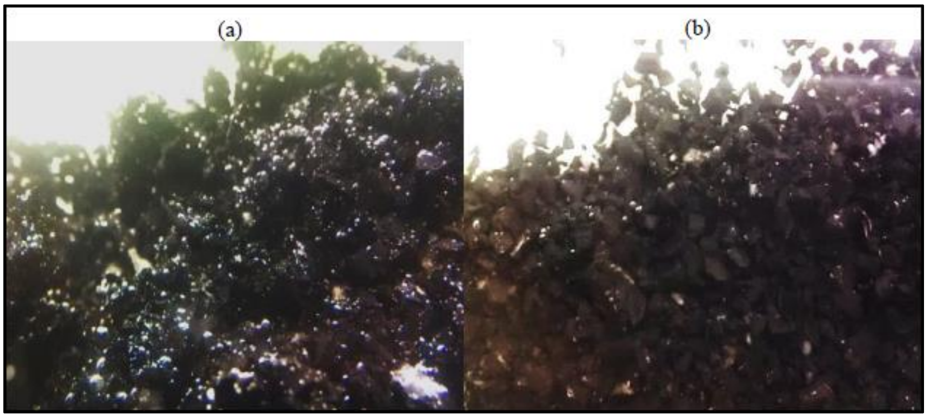

Figure 6: (a) Air bubbles attached to rubber instantly after submerging in water, (b) Most air bubbles released from rubber 24 hours after submerging in water (Mohammadi et al. 2014).

Over vibration of the concrete mixture can result in segregation of the aggregates with the rubber particles floating to the surface of the mix (Ganjian et al. 2009). There are three explanations for this behaviour. The water repelling nature of rubber particles, often termed hydrophobic behaviour (Youssf et al. 2014; Siddique & Naik 2004). Secondly, the difference between the SG of rubber particles and other aggregates, and finally air bubbles that attach to the rubber particles (Mohammadi et al. 2014).

Within this investigation I will use a relatively new treatment method that involves soaking rubber particles in water for 24 hours. Mohammadi et al. (2014) found that during the 24 hour period of water soaking air bubbles attached to the rubber gradually release and the water repelling nature of rubber can be drastically reduced (Mohammadi et al. 2014).

2.5 Summary

The term rubberised concrete includes all types and sizes of recycled rubber. Although substantial research has been conducted on the idea of incorporating recycled rubber in concrete, only one investigation has been performed on the use of water soaking as a rubber treatment method. The aim of this research is to extend the knowledge of CRC characteristics when rubber particles have been chemical or water treated. Investigating the challenges linked with the creation of concrete mix with crumb rubber and implementing techniques to alleviate the challenges are of high importance. Challenges include the identification of an optimised rubber content and rubber treatment method for the concrete mixture. Establishing an experimental relationship for predicting the strength properties of CRC by considering the effects of rubber content and rubber particle treatment methods is essential.

CHAPTER 3

3.0 METHODOLOGY

3.1 Introduction

The main objective of this study is to investigate the characteristics of several CRC concrete mixtures and select a suitable CRC design mixture. Two replacement levels of crumb rubber, 15% and 20% by volume of fine aggregate with a size of 0.750mm will be used to create specimens in this investigation. In this chapter I will detail the methodologies used to create and evaluate the fresh and hardened properties of the various CRC specimens.

3.2 Research Materials

The purpose of this section is to identify the different constituents of rubberised concrete and other additional materials used for this research. Several concrete mixtures have been prepared using resources with detailed properties which will be clarified below.

3.2.1 Natural Fine and Coarse Aggregates

The natural aggregates used have both been sourced locally. Natural river gravel with a nominal dimension of 7mm has been used as coarse aggregates. The available supply of sand is a well graded mixture of fine to coarse natural river sand. All of the natural aggregates used for this experimental study fulfil the concrete grading requirements of the Australian Standard AS 2758.1 (AS 2758.1 2014). The particle size distribution of fine and coarse aggregate testing was followed in accordance with Australian Standard AS1141.11.1 (AS1141.11.1 2009) and the results are shown in figure 12.

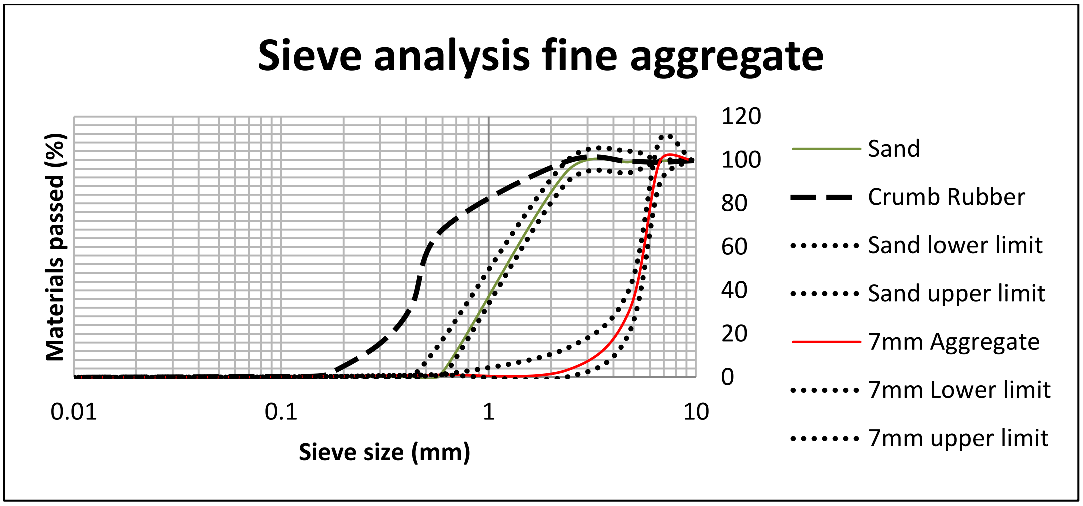

Figure 7: Fine, coarse and rubber aggregate particle size distribution and boundary limits as per AS2758. 1 (AS2758.1 2014)

All fine and coarse aggregates were prepared to surface saturated dry (SSD) condition prior to mixing. The SG and saturated surface dry density of aggregate has been determined in accordance with Australian Standard AS1141.5 (AS1141.5 2000). The results of these tests are presented in table 2.

Table 2: Properties of fine and coarse aggregate used in this research

	Specific gravity	**Density (kg/m^3)**
Fine Aggregate	2.523	2474
Crumb Rubber	1.17	1159
Coarse Aggregate	2.77	2504

3.2.2 Crumb Rubber Aggregate

Only one grade of crumb rubber has been used in this research. Ground rubber has been obtained from the company Tyrecycle located in Melbourne. The size of crumb rubber aggregates obtained from the company is 0.750mm and the results of the particle size distribution analysis are shown in figure 12.

In order to find the correct quantity of crumb rubber for the concrete mixture, determining the SG of crumb rubber correctly is essential. The SG is defined as the ratio of rubber weight in air to the weight of an equal volume of water, which includes the weight of water within

the voids. Following AS 1141.5 (2000), water with a temperature of 23±3°C has been used. Four series of crumb rubber specimens have been tested in this investigation.
Previous research conducted by Sukontasukkul & Tiamlom (2012); Sgobba et al. (2010) reported air bubbles attaching to rubber when added to water. The air bubbles are considered a source of inaccuracy in the calculation of SG for the rubber particle. It was found that the air bubbles attached to the recycled rubber particles resulted in floating rubber particles. An investigation performed by Mohammadi (2014) used two methods to remove trapped air bubbles from the rubberised concrete mixture. The first method involved soaking the rubber particles in water while the second involved soaking in a de-foaming agent mixed with water. Mohammadi (2014) determined that there was a negligible difference between the two methods. For this reason the method of soaking rubber in water has been adopted.

All test procedures for materials were followed in accordance with Australian Standards AS1141.5 (AS1141.5 2000). The SG was conducted 24 hours after mixing rubber and liquid. The final value for the SG of the crumb rubber used in this investigation is displayed in table 2.

3.2.3 Admixtures

Only one type of chemical admixture has been used throughout the study. A Polycarboxylic ether type super plasticizer has been used as a water reducing agent. Water-reducing admixtures are groups of products that are added to a concrete mix for achieving certain workability. The same level of workability can be attained at a reduced water-cement ratio using water reducing admixtures (Mailvaganam & Noel 2002; Ho et al. 2009; Yousff et al. 2014). Furthermore, water reducing admixtures are used to improve the quality of concrete by reducing water content of mix and also obtaining a specified higher strength at the provided lower water to cement ratio. The product selected for use in this research is Pantarhit manufactured by Ha-Be Betonchemie GmbH & Co. KG.

3.2.4 Water

The selected water for this research is clean drinking water used at room temperature and utilised for all mix series. In addition, the volumes of water have been calculated for each concrete mixture based on the design water to cement ratios and moisture conditions of the aggregates.

3.3 Identification of Specimens

This research involves the assessment of various CRC mixtures in order to find the optimum content of crumb rubber, which should be added to the mix series to achieve the best performance. To determine the best performance, different CRC mixtures have been prepared and tested. The CRC mixtures have been categorized based on the purpose by which they were prepared.

Firstly, four sets of trial mixes have been prepared for investigating the suitability of the selected ranges of crumb rubber content. The mix identification for each design provides details regarding the three mix components which are described here with, [mix type], [rubber content], [method of treating rubber]. The prefix (T) represents the trial specimens and (C) represents the additional specimens that were created for further data. The rubber content is described by a value which represents the percentage of natural fine aggregate replaced by crumb rubber. Finally, the suffix describes the rubber treatment method. (N) is used for no treatment, (W) for water soaking and (C) for chemical treatment. For instance, T/20/W describes a “Trial” mix with a crumb rubber content of 20% by volume of fine aggregate prepared by water soaking technique (W).

All the mix designs are shown in detail in table 3 with their codes and corresponding constituents. All mix designs have a single water to cement ratio (WC) of 0.35, superplasticiser of 0.5% (by cement weight) and cement content of 431kg/m^3.

Table 3: Properties of trial CRC mixtures

Mixture ID	W/C	Cement (kg/m^3)	Sand Vol (%)	Sand Weight (kg/m^3)	Coarse Aggregate 7mm (kg/m^3)	Water (kg/m^3)	Rubber Vol (kg/m^3)	Rubber Weight (%)	Superplasticizer (kg/m^3)	Total (kg/m^3
Control T	0.35	431	100	633	1270	158	0	0	2.125	2492
Control C	0.35	431	100	633	1270	158	0	0	2.125	2492
T/15/N	0.35	431	85	537	1270	158	15	30.9	2.125	2427
T/20/N	0.35	431	80	506	1270	158	20	43.5	2.125	2409
T/20/C	0.35	431	80	506	1270	158	20	43.5	2.125	2409
T/20/W	0.35	431	80	506	1270	158	20	43.5	2.125	2409
C/20/W	0.35	431	80	506	1270	158	20	43.5	2.125	2409

3.4 Rubber Treatment Procedures

Many investigations have been conducted on CRC, however most introduce rubber particles into the concrete mixture using the same methods as ordinary concrete aggregates.

Many researchers have reported that NaOH treatment of rubber particles increases the strength of concrete (Balaha et al. 2007; Pelisser et al. 2011; Youssf et al. 2014). However, for this investigation only one of the four CRC specimens (T/20/C) will be treated with NaOH. This is primarily due to the treatment procedure being expensive and difficult to implement on an industrial scale.

Another treatment method of water soaking will also be investigated as a possible alternative for NaOH treatment. The water soaking method is a practical and cost effective method for increasing the strength of concrete. Similarly, only one of the four CRC specimens (T/20/W) will be treated by water soaking. Both of the proposed treatment methods will be compared with a non-treated control sample (T/20/N) to evaluate the performance of the two methods.

The following sections will be used to list the procedures and techniques for surface modification treatment of rubber. First, the procedure for NaOH treatment will be outlined, followed by the procedure for water soaking treatment method.

3.4.1 Sodium Hydroxide Treatment (NaOH)

The following procedure for NaOH treatment has been developed by (Yousff et al. 2014). The procedure began with the required amount of rubber particles being washed by tap water to remove dust and impurities. They are then submerged in a 10% NaOH solution for

30 mins in a container. Finally, the rubber particles are washed again by stirring in water until its pH becomes 7 and left to air dry. To avoid a negative effect to the durability of the concrete it is essential to remove any remaining NaOH solution in the final wash. The total time required to completely remove the NaOH from the rubber particles is approximately 30 minutes. Figure 13 shows the different stages of NaOH treatment.

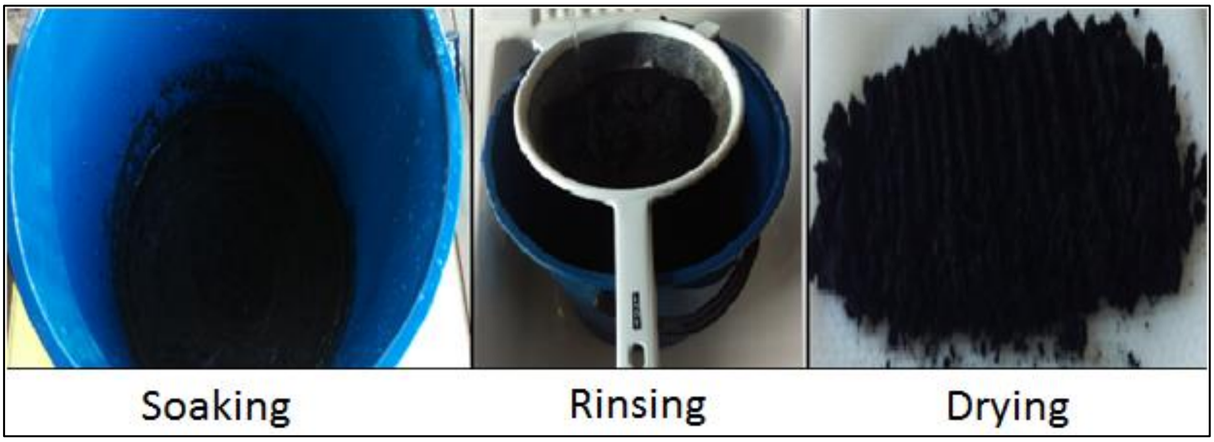

Figure 8: Different stages of NaOH treatment

3.4.2 Water Soaking treatment

The following procedure for water soaking treatment has been developed by Mohmmadi (2014). The procedure begins with mixing the required amount of rubber particles with water and stirring. After stirring the mixture for 5 mins it is left aside for 12 hours. At the 12 hour interval the mixture is re-stirred for another 5 mins and left aside for another 12 hours. After 24 hours the crumb rubber particle are rinsed off and left to air dry for 30 mins prior to mixing into CRC mixture.

3.5 Specimen preparation

3.5.1 Trial specimens

Concrete mixtures used in this investigation are prepared with and without rubber aggregate. These mixtures are used to conduct the experimental research required for this dissertation. The experimental concrete batches consist of a single control concrete mixture with no replacement of the natural fine aggregate, as well as a total of four rubberized concrete mixtures prepared with replacements of the fine aggregate with crumbed rubber of 15% and 20% by fine aggregate volume.

The concrete mixture design has followed the procedure outlined in the Australian standards AS1012.8.1 (2014) and AS1012.8.2 (2014). The cement, water, and coarse aggregate proportions have been kept constant for both the control mixtures and the rubberized concrete mixtures. The fine aggregate has been replaced with selected proportions of the crumb rubber aggregate to form the experimental batches of rubberized concrete.

Thorough mixing is essential for the total blending of materials to ensure the surface of all aggregate particles are covered with water cement paste and that the mix is homogenous to obtain uniform properties throughout the entire concrete mixture.

Mixing procedure developed by Yousff et al. (2014) has been used for the control mixes:

- Mix dry sand and gravel for one minute.
- Add half of the water and mix for one minute.
- Rest for two minutes.
- Add cementitious materials, water, and admixtures, and then mix for two minutes.

The mixing procedure for the CRC mixes is the same, except that the rubber aggregate has been first mixed with dry cementitious materials for one minute in an external container. The purpose of this is to increase the rubber-cement surface bond, which is one of the main issues affecting the strength of CRC.

The fresh concrete mixture is subjected to a slump test before being placed into concrete casting cylinders and beam moulds in accordance with (AS1012.8.1 2014; AS1012.8.2 2014) and left to set for 24 hours. After 24 hours the specimens are removed from the cylinder and beam moulds and submerged in a large curing tank (figure 14) to cure for 28 days at a temperature of 24°±2° before the hardened concrete properties testing are conducted. Three specimens have been prepared for each concrete design mixture.

Figure 9: Specimens submerged in curing tank set to 24°±2°.

3.5.2 Additional specimens for further data

Three additional beam samples and cylindrical samples have been created for both the control concrete mixture and the CRC mixture. The extra samples served two purposes, to collect more accurate data for stress/strain curves which would help identify the modulus of elasticity as well as verifying the results obtained in preliminary testing. Verifying the data ensured that the samples have been created using a consistent CRC mix design. The specimens consisted of one control mixture with no crumb rubber replacement and one specimen with 20% crumb rubber replacement with water soaking treatment. The two specimens have been identified by the codes 'Control C and C/20/W' respectively.

3.6 Methods of Testing for Trial Specimens

The fresh and hardened properties of all mix series have been assessed using procedures found in Australian standards AS1012.3.1, AS1012.9 and AS1012.11 (AS1012.3.1 2014; AS1212.9 2014; AS0012.11 2000). Tests that have been carried out for evaluation of fresh and hardened properties of the main mixes are outlined in Table 4.

Table 4: List of tests and the relevant Australian Standards

Test	Type	Standard
Particle size distribution	Fresh	AS1141.11.1
Particle density/ water absorption	Fresh	AS1141.5
Slump	Fresh	AS1012.3.1
Density	Hardened	AS1012.12.1
Compressive strength	Hardened	AS1012.9
Flexural strength	Hardened	AS1012.11
Modulus of Elasticity	Hardened	AS1012.17

In the following sections, the test methods applied for this research are explained briefly.

3.6.1 Slump

Workability of fresh concrete is assessed using slump test. This method is detailed in Australian Standard AS1012.3.1 (AS1012.3.1 2014). The slump test uses a cone like bucket with the dimensions shown in Figure 16.

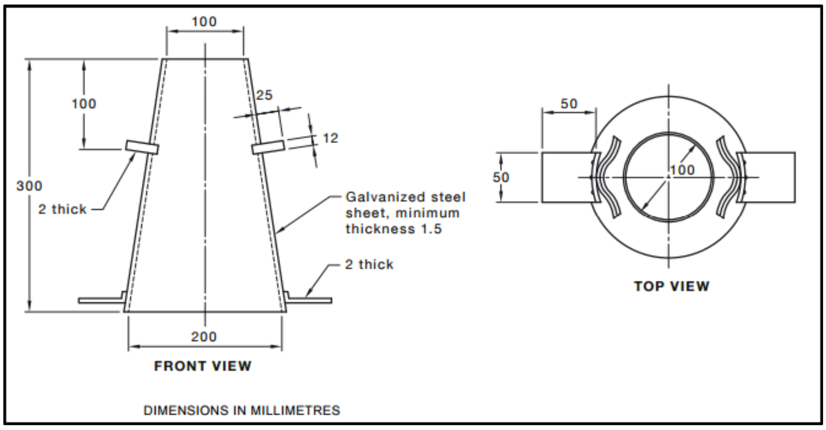

Figure 10: Mould used for slump test (AS1012.3.1 2014)

There are four different slump shapes that could occur when conducting a slump test as shown in figure 17. If the slump shape is even all round, it is called a true slump. A zero slump shape describes a concrete mix with very low workability. A collapsed slump occurs when the concrete mixture has a lack of cohesion which could be caused by segregation of aggregates. Shear slump occurs when one half of the cone slides down an inclined plane and is also caused by a lack of cohesion. If a shear slump occurs the slump test should be performed again.

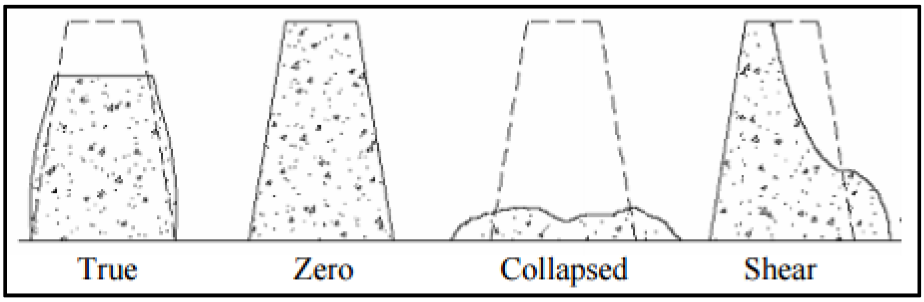

Figure 11: Four types of slump shapes (Kochler & Fowler 2003)

3.6.2 Density

Measuring the density of concrete is conducted by dividing the mass of fully compacted concrete by its volumetric capacity in the plastic state. The test procedure for measuring concrete density is described in Australian Standards AS1012.5 (AS1012.5 2014). Four measurements of the samples width, depth and length have been taken with Vernier callipers and steel rule and the average sample dimensions have been determined. Each sample has been removed from the curing tank at 28 days and been completely dried prior to testing.

3.6.3 Compressive Strength

The compressive strength test is considered an easy test to execute and is performed on hardened concrete. Furthermore, many of desirable characteristics of concrete rely on its compressive strength. According to the Australian Standards AS1012.9 (AS1012.9 2014), cylindrical specimens should be prepared for compressive strength testing as shown in figure 18 below.

The compressive strength tests have been performed in accordance with the procedure taken from Australian Standard AS1012.9 (AS1012.9 2014). All the compressive strength tests have been undertaken on cylindrical specimens of 100 mm diameter with 200 mm length. A rubber cap has been installed prior to each test.

The two batches of cylindrical specimens have been subjected to compressive strength testing. Firstly the (T) series specimens have been tested at the University of Southern Queensland, Springfield campus using a 3000 kN compression machine shown in figure 18. Due to substandard stress/strain data collected by the data acquisition equipment at Springfield, the modulus of elasticity could not be determined. The decision was made to cast a second batch of samples ('C' series) to obtain good quality stress/strain data in an attempt to determine the modulus of elasticity.

Figure 12: Springfield campus compressive strength machine

The second batch of samples have been tested at the University of Southern Queensland, Toowoomba campus using the SANS compression machine shown in figure 19. The samples have been tested in the same manner as the 'T' series specimens however a loading rate of 1mm per minute was adopted.

Figure 13: Toowoomba campus SANS machine

Finally, the compressive strength of all the specimens has been determined by dividing the maximum force the specimens undertake by the cross sectional area of specimens. The compressive strength at the age of 28 days has been measured for all specimens. Three cylinders from each mix design have been used for testing with the average result of compressive strength being recorded.

3.6.4 Flexural Strength

To determine the flexural strength of CRC, tensile strength tests have been performed. The test involves subjecting an unreinforced concrete prism to a four-point flexural load until failure. The ultimate flexural strength of each test specimen has been calculated using the elastic theory equation shown below in equation 1. Three beam specimens from each mix design have been used for testing with the average maximum flexural strength being recorded.

The flexural strength of the trial (T) specimens has been obtained by using a four-point bending machine at the University of Southern Queensland, Springfield campus. 100×100×350 mm prisms have been loaded at a rate of 1 MPa per minute until failure, according to the test procedure set out in the Australian Standard AS1012.11 (AS1012.11 2000). The beam span adopted for this study is 315mm.

The mid-span deflection of the flexural specimens has been determined by laser displacement sensor measuring the load assembly travel distance while the two point loads have been applied. Accurate mid span deflection of flexural specimens are determined by positioning the laser displacement sensor under the specimen at the mid span to directly measure the specimen deflection. However the machine at the Springfield campus was unable to be set up with this test arrangement because of concerns of damaging the laser displacement sensor when the specimen failed. Figure 20 shows the arrangement of the 4-point bending test conducted at the Springfield campus.

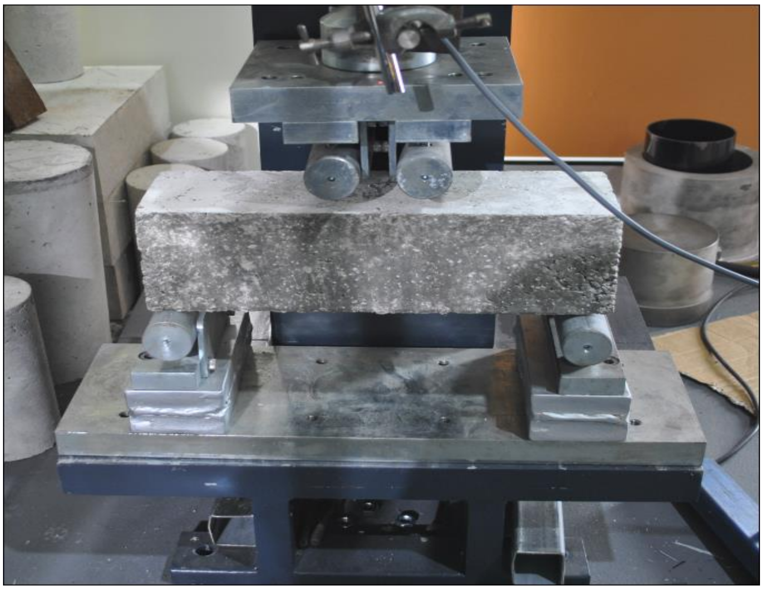

Figure 14: Flexural strength test arrangement (AS1012.11 2000)

The flexural strength of the (C) specimens has been obtained using the MTS Insight-100 Electromechanical machine with a four-point bending arrangement at the University of Southern Queensland, Toowoomba campus. The same test procedure as Springfield has been adopted however a loading rate of 1mm per minute has been used. The ultimate flexural strength of the (C) series specimens has been calculated using the same method as the (T) series specimens using the formula shown in equation 1.

The flexural stress is calculated as:

$$f_{ctf} = \frac{3F(L - L_i)}{2bd^2}$$

Equation 1

Where *fctf* is the tensile strength in MPa, *F* is the maximum applied force in kN, *L* is span length in mm, *Li* is the length of the loading (inner span), b is the average width of the specimen at the section of failure in mm and d is the average depth of specimen at the failure section in mm.

3.6.5 Modulus of Elasticity

The modulus of elasticity is defined as a gradient of the line drawn between two specific points on the stress-strain curve AS1012.17 (AS1012.17 1997). The Australian Standard AS1012.17 (1997) addresses these two points and the required data. They should be recorded as follows:

a) Point g1, where the measured strain is 50 micro-strains and the corresponding stress to this strain.
b) Point g2, where the measured stress is equivalent to 40% of the maximum compressive strength and its corresponding strain.

In order to measure the longitudinal strain, a standard compressometer will be used. The test will be conducted under a controlled load rate in a 3000 kN compression testing machine with load rate of 20 ± 2 MPa per minute. The modulus of elasticity of the concrete sample will be calculated using the following formula:

$$E_c = \frac{G_2 - G_1}{\varepsilon_2 - 50 \times 10^{-6}}$$

Equation 2

Where *Ec* is the concrete modulus of elasticity in MPa, *G2* is the test load (as described above), divided by the cross-sectional area of the specimen in MPa, *G1* is the applied load at a strain of 50×10-6 divided by the cross-sectional area of the specimen in MPa and *ε2* is the strain corresponding to deformation at test load in micro strain.

A graphical approach can also be adopted to determine the modulus of elasticity. The modulus of elasticity is represented by the gradient of the line drawn between two points on the linear portion on the stress-strain diagram.

Using the formula shown in equation 3, the value for modulus of elasticity can be obtained.

$$E = \frac{\sigma}{\varepsilon}$$

Equation 3

Where *E* is the concrete modulus of elasticity in MPa, s is the test load, divided by the cross-sectional area of the specimen in MPa, ε is the strain corresponding to deformation at test load in micro strain.

CHAPTER 4

4.0 RESULTS AND DISSCUSSION

4.1 Introduction

This chapter presents the experimental results from the various tests conducted in this investigation. There have been two different stages of experimentation during this study. The first stage is selecting a suitable CRC mixture from four available mix designs consisting of various rubber contents and treatment methods. The second stage involves testing additional samples in order to verify the preliminary specimens. Chapter 4.2 addresses the two treatment methods used in this research and highlights observations made in the investigation. Chapter 4.3 focuses on results of the testing performed on trial (T) and (C) specimens with a detailed analysis of test results.

4.2 Rubber Treatment Methods

4.2.1 Sodium Hydroxide (NaOH)

It has been observed that when introducing the crumb rubber into the NaOH solution, the majority of the crumb rubber sat on top of the fluid. The method set out by Youseff et al. (2014) did not specify how often the rubber/ NaOH solution was mixed. For this investigation I mixed the rubber/ NaOH solution for the entire thirty minutes to enable the best possible treatment of the rubber. Furthermore the time taken for the rubber particles to return to a pH of seven was only 20mins. This is possibly due to a faster rate of water washing the rubber particles.

4.2.2 Water soaking

Like the NaOH treatment method, there have been issues with mixing rubber with fluid. After initially adding the rubber to the water approximately 70% of the rubber particles floated on the surface.

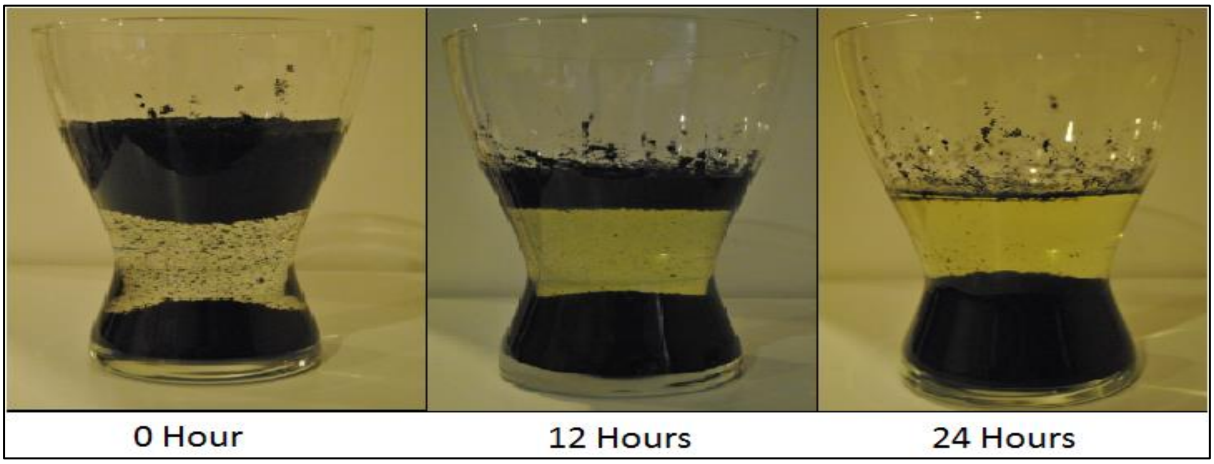

Figure 15: The three stages of water treatment (0 hrs, 12hrs and 24 hrs)

Figure 22 shows that the longer the rubber has been left in the water the more particles sunk to the bottom, indicating the hydrophobic behaviour of rubber particles can be overcome. After 24 hours, almost all the rubber had sunk.

This treatment method is easier to execute, is a lot safer and shows an increase of compressive and flexural strength when compared to the chemical treatment which will be discussed in section 4.3.3 and 4.3.4.

4.3 Trial Specimens

Several trial mixes have been prepared in order to determine the most suitable CRC mix design. The primary aim of assessing the various CRC design mixes is to determine the fresh and hardened characteristics of the CRC. The fresh and hardened characteristics will be discussed in the following sections.

4.3.1 Slump

The workability of the different mix designs has been determined using the slump test according to AS1012.3.1 (AS1012.3.1 2014).

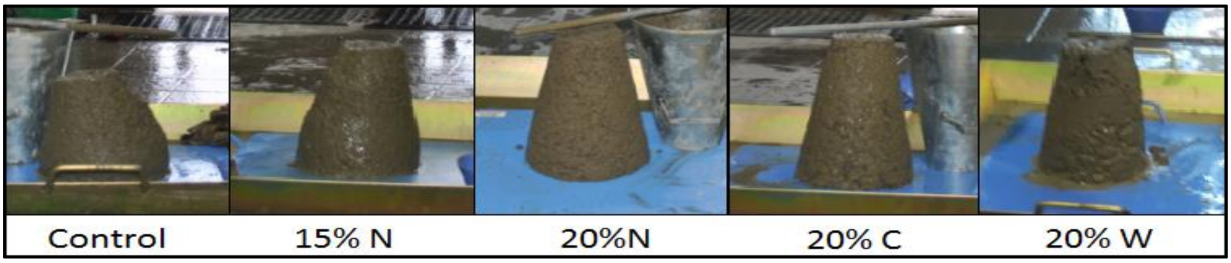

Figure 16: Workability of trial CRC mixtures with various rubber content and treatment methods

As shown in figure 23 & 24, CRC mix designs prepared with 15% crumb rubber show good workability with lower workability being observed for 20% crumb rubber content. Slump loss of approximately 20% and 53.5% at crumb rubber replacement levels of 15% and 20% respectively are observed when compared to the control. The slump values are significantly reduced for increasing rubber contents as shown in Figure 24.

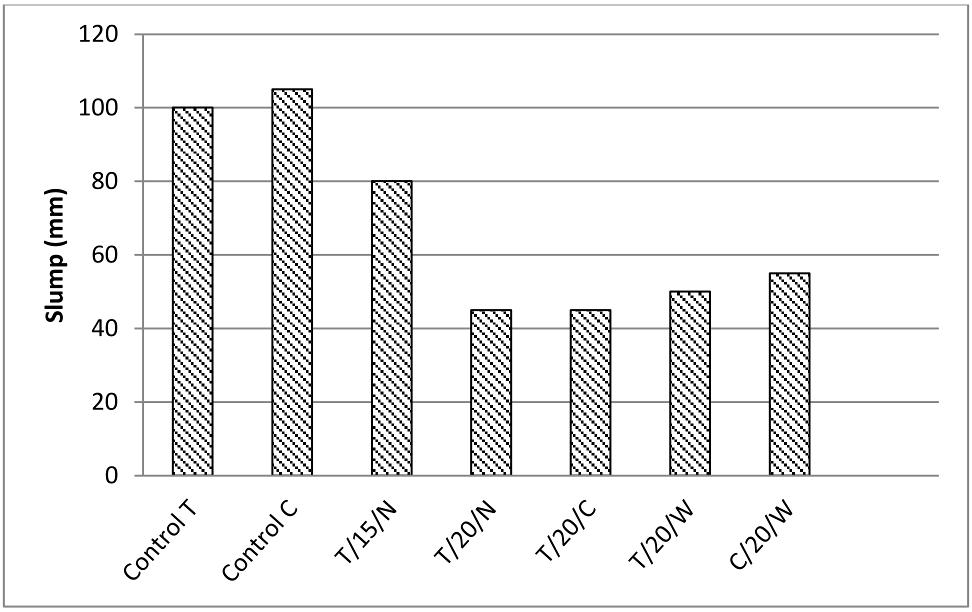

Figure 17: Slump (mm) for all specimens with various % of crumb rubber content and treatment methods

4.3.2 Density

As shown in Figure 25 the rubber content increases as the density of CRC decreases. As the crumb rubber has a much lighter density than sand a reduction of density of the CRC is expected. Furthermore the decrease in density for CRC is consistent with findings outlined in the literature reviewed in this investigation.

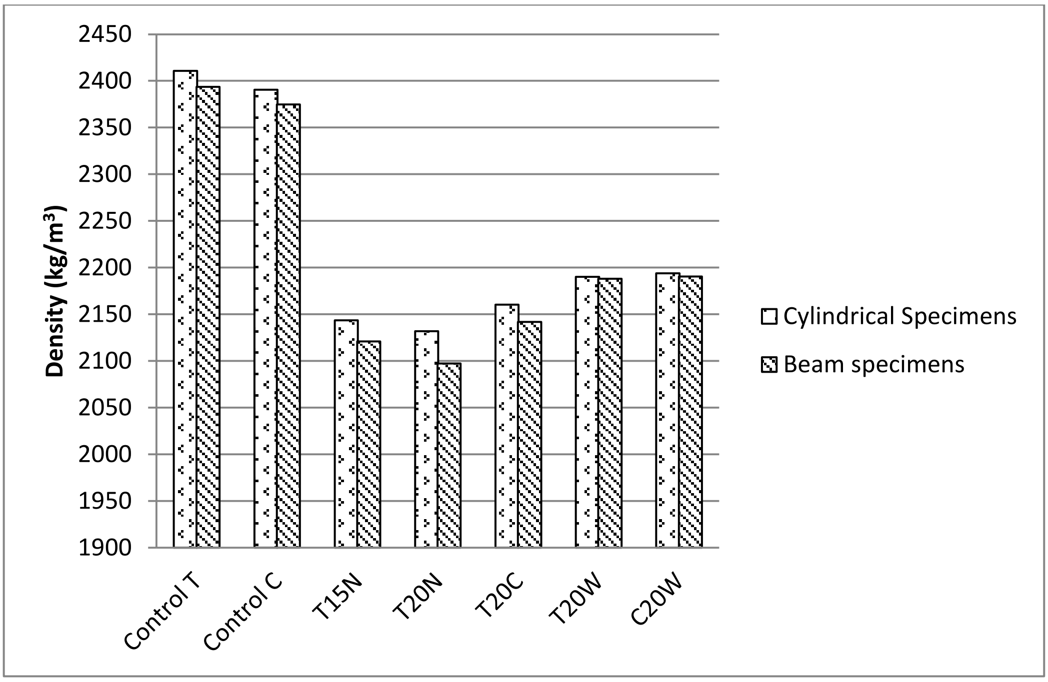

Figure 18: Density of cylindrical and beam specimens

Treated rubber CRC mixtures had slightly higher densities when compared to the untreated CRC mixtures. As explained in section 3.2.2, air bubbles attach to the untreated rubber and get introduced into the CRC mixture. The excess air present in the untreated CRC mixtures is characterised by low density, low compressive strength and low flexural strength which will be discussed in 4.3.3 and 4.3.4. Furthermore, there is a strong correlation between the density of the cylindrical and beam specimens and also between ‘Control A and Control C’ and ‘T/20/W and C/20/W’ specimens indicating consistency with CRC mixtures.

4.3.3 Compressive Strength

Compressive strength tests have been performed at 28 days and the results for each of the mix designs are shown figure 26.

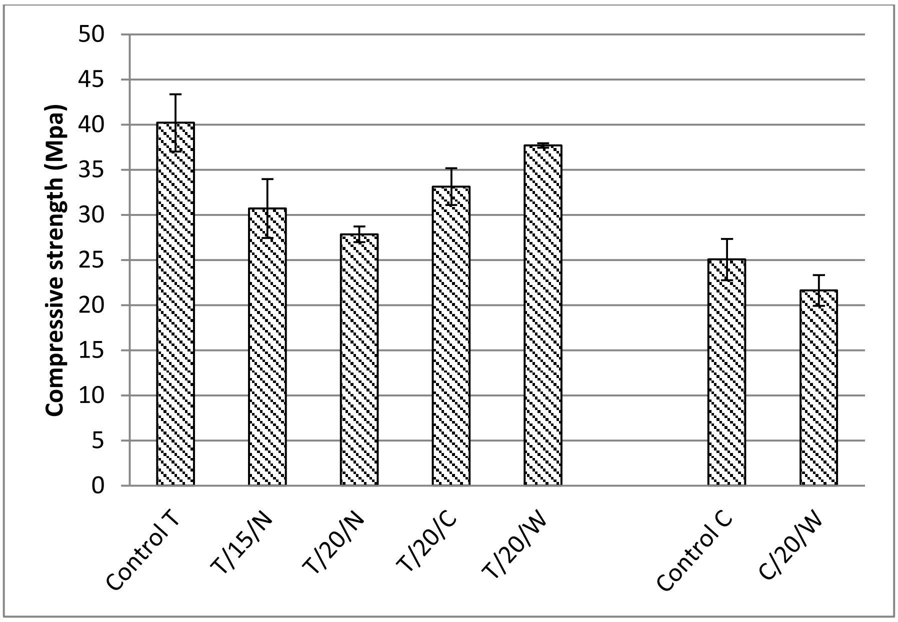

Figure 19: Average compressive strength for the trial specimens

The compressive strength tests performed on the trial specimens shows that as the rubber content of non-treated rubber increases the compressive strength decreases. For each 5% increase in crumb rubber content there is a compressive strength loss of approximately 3.5 MPa with a maximum compressive strength loss of 32% for the 20% crumb rubber content when compared to the control mix.

Crumb rubber subjected to treatment methods prior to mixing exhibited greater compressive strength when compared with no treatment. The effect of rubber pre-treatment using NaOH solution on compressive strength has been determined through comparison of the results of design mixture T/20/C (NaOH treatment) and T/20/N (untreated).

As shown in Figure 26 the compressive strength increase due to NaOH pre-treatment is approximately 16%. The effect of rubber pre-treatment using the water soaking method has been determined using the same comparison methods as the NaOH. The compressive strength increase due to water soaking treatment is approximately 26.5%.

The cylindrical (C) series specimens have been separated in figure 26 to highlight the inconsistent results with the trial (T) specimens. The (C) series specimens have been tested on the Toowoomba campus SANS machine. Control C and C/20/W have a compressive strength of 46% and 45% lower than the corresponding (T) series specimens.

The (C) series flexural specimens correlated well to the (T) series flexural specimens. This seems to indicates an error occurred while operating the SANS machine for the (C) series compression specimens.

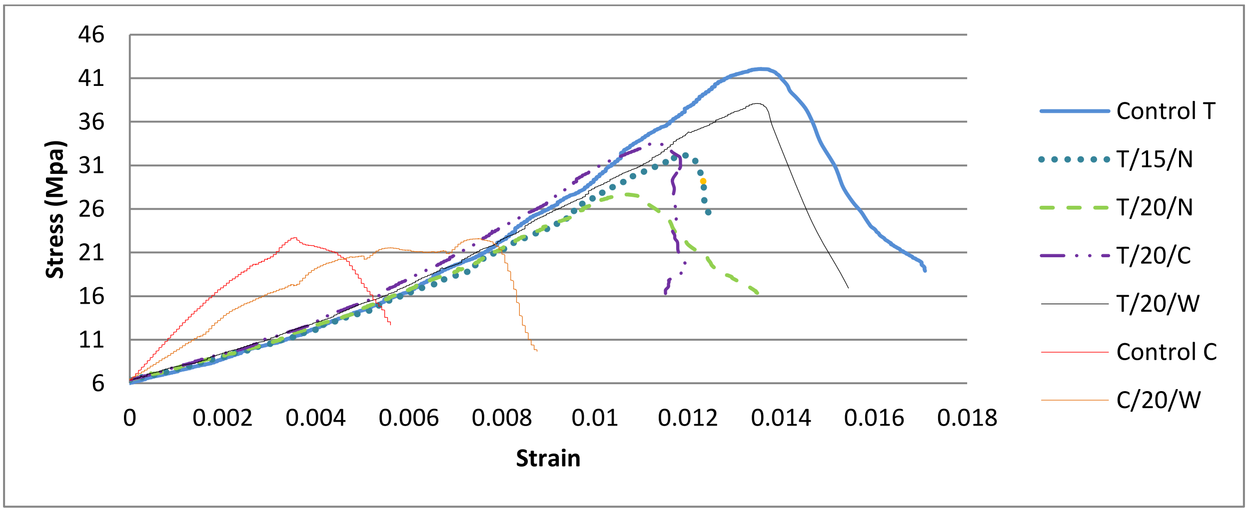

Figure 20: Compressive stress/strain curves for the trial (T) and (C) series CRC mix designs

Figure 27 shows a large difference between the stress/strain curve for the trial (T) series and the (C) series specimens. Although the maximum compressive strength appears to be incorrect, the stress/strain curve for the (C) series specimens better reflects a typical stress/strain curve for concrete. One possible explanation for the discrepancy can be the different methods used to apply the load to the specimens on the different machines. The load for the test specimens on the SANS machine in Toowoomba has been applied in terms of deflection (1mm per minute) while the Springfield test specimens have been loaded in terms of force (20 ± 2 MPa per minute). The combination of rubber caps and the loading method for the (T) series compression specimens tested at Springfield is one possible explanation for the uncharacteristic stress/strain diagram shown in figure 27.

4.3.4 Flexural Strength

The flexural strength tests have been performed at 28 days using a four point bending machine. The results of the four point bending tests for each of the mix designs are shown in figure 28.

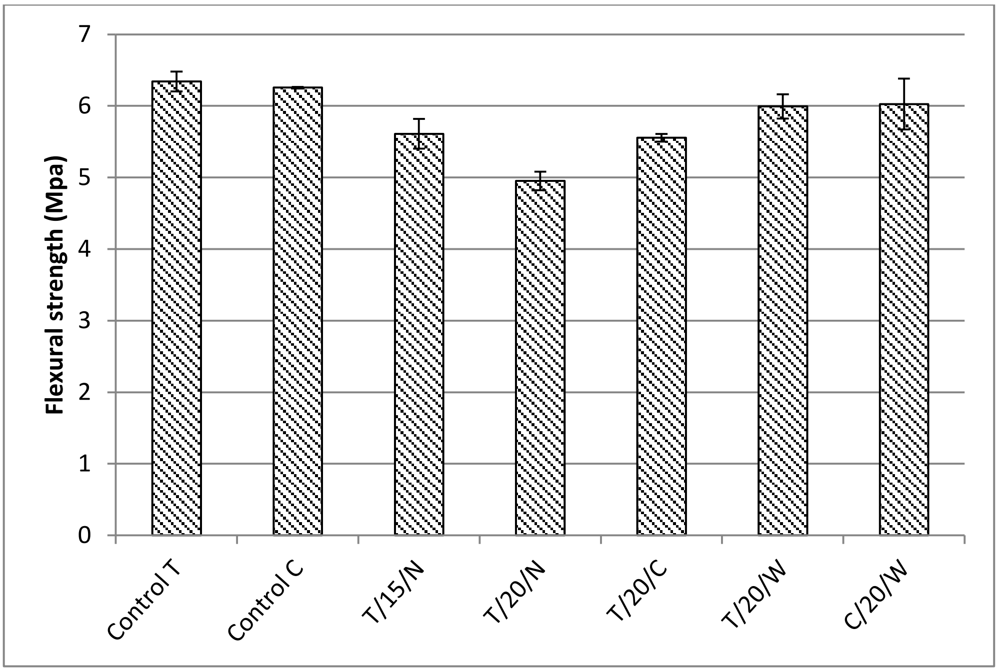

Figure 21: Average flexural strength for the trial specimens

As anticipated, the flexural strength loss seen in the CRC for untreated rubber is consistent with the compressive strength losses.

Following the same method of comparison as compressive strength, the T/20/N (untreated) specimen will be compared with the T/20/C and T/20/W (treated) specimens. In Figure 28 is shown the flexural strength increase due to NaOH pre-treatment by approximately 11%. An increase of approximately 15% is also recorded for the water treatment method. A loss of 8% flexural strength can be observed between the T/20/W and C/20/W and the control.

The stress-strain curves for all specimens are presented below in figure 29. For each mix design, only one of the three available stress-strain curves is presented to allow easier comparison of results.

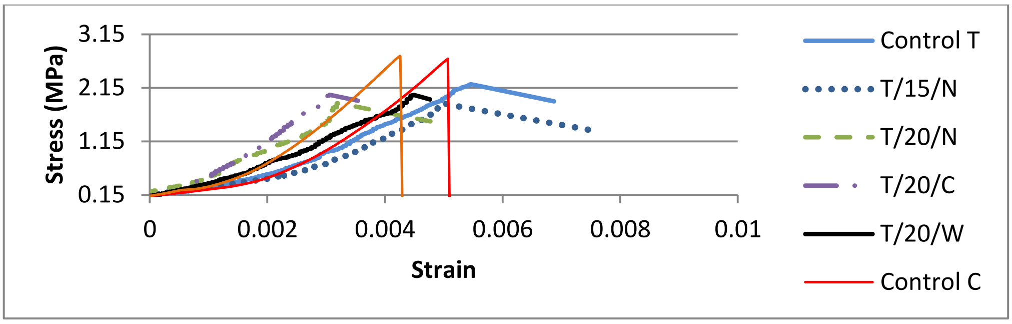

Figure 22: Flexural stress/strain curves for the trial (T) and (C) series CRC mix designs

4.3.5 Modulus of Elasticity

After performing the compressive and flexural strength testing on the (T) series specimens at Springfield, analysis of the recorded data revealed that the information collected is poor and the modulus of elasticity cannot be determined. A second batch of specimens (C series) has been cast to obtain good quality stress-strain data leading to the determination of the modulus of elasticity. After analysing the data from Toowoomba it is found that the stress-strain diagram produced by the SANS machine has not been sufficient to find the modulus of elasticity. The modulus of elasticity has therefore not been able to be obtained in the investigation.

CHAPTER 5

5.0 CONCLUSIONS

5.1 Conclusions

The purpose of this research is to provide data that can be used for preparing rubberised concrete. This study was conducted to assess the fresh and hardened characteristics of CRC where the rubber particles have been treated by using NaOH, as well as a relatively new water soaking method. The following conclusions can be drawn based on the results achieved in this research:

• The two rubber treatment methods have been compared and evaluated. The results in this research show that the water soaking method performed better than the more common chemical treatment method using NaOH. The benefits of the water treatment method are (a) inexpensive and easy to implement into industry; (b)it can resolve issues relating to entrapped air, and (c) it can help create a CRC mixture that exhibits better homogeneity.

• A comparison of the chemical treated specimens and water soaked specimens has been made with an untreated rubber specimen. For chemical and water soaked specimens the compressive strength increase by 16% and 26 respectively. The flexural strength increase is not as significant at 11% and 17% for chemical and water soaked treatment methods.

• Workability of CRC mixtures decreases when adding larger volumes of untreated rubber. For the equivalent volumes of rubber, both of the treated methods have slightly more workability. This is caused by the additional moisture from particles that have been soaking in the treatment fluid.

• The density of the CRC mixtures decreases with increasing amounts of untreated crumb rubber. This is due to air particles attaching to untreated rubber particles which then get introduced to the concrete mixture. The density for both the treated specimens is slightly greater. This is due to the treatment process releasing air particles for the rubber prior to being introduced to the concrete mixture.

Considering the hardened characteristics of CRC determined in the investigation, the method of water treating is shown to produce the most promising results. The method is simple, cost effective and easy to implement.

5.2 Recommendations for future investigations

This research has made significant steps towards contributing data for treatment methods of rubber and optimised CRC mix designs. Several aspects of CRC that still require further investigation include:

• Determination of premature deterioration over longer periods of time due to chemical rubber treatment. Investigation into the durability of chemical treated CRC is necessary to ensure the CRC is not compromised over time.

•The water soaking method presented in this research increases compressive strength by reducing the amount of air particles that attach to the crumb rubber. Further research will be needed to determine whether the compressive strength increase for the chemical treatment is due to a better bond between rubber and cement as suggested by the literature or if the strength increase is due to reduced entrapped air from being submerged in the chemical solution.

• Treatment methods in this research were only investigated separately. A rubber treatment method that combines the benefits of the two treatment methods, for example, 24 hours water soaking followed by 30 mins chemical treatment, could be beneficial.

• This research investigated the introduction of crumb rubber into concrete with a particles size of 75 microns. Although literature reviewed in this research suggests larger rubber particle sizes have a more detrimental effect on the compressive strength of concrete, they do not take into account the water treatment method and possibly a dual treatment method using both water and chemical treatment.

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APPENDIX A. PROJECT SPECIFICATION

ENG4111/4112 Research Project

Project Specification

For: Brendon Heath

Title: Investigation into flexural characteristic of cold formed steel filled with rubberised concrete.

Major: Civil

Supervisors: Assoc Prof Yan Zhuge

Sponsorship: Tyrecycle Pty Ltd

Enrolment: ENG4111 – ONC S1, 2016

ENG4112 – ONC S2, 2016

Project aim: To determine the mechanical characteristics of crumb rubber concrete (CRC) using various pre-treatment methods.

Programme: Issue B, 23rd September 2016

1. Research existing crumb rubber concrete (CRC) mix designs.
2. Research the flexural properties of Bondek stay in place formwork when used with standard concrete.
3. Pre-treat crumb rubber using chemical and water soaking techniques.
4. Mix, cast and store samples of CRC using pre-determined mix design.
5. Perform axial compression and four point bending tests on CRC samples to determine mechanical characteristics.
6. Mix, cast and store a second set of CRC samples identical to item 4 for comparison.
7. Perform axial compression and four point bending tests on second set of CRC samples to compare with initial testing (item 5).

If time and resources permit:

8. Mix, pour and store Bondek samples using best performing CRC design mix.
9. Perform four point bending tests on Bondek optimised CRC to determine strength characteristics.