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Title:

Investigation on the Use of Crumb Rubber Concrete (CRC) for Rigid Pavements

By:

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Certificate of Authorship/Originality

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

Iman Mohammadi

June 2014

Abstract

In many countries around the world, the adverse environmental impacts of stockpiling waste tyres have led to investigate alternative options for disposal of waste tyres. One option to reduce this environmental concern is for the construction industry to consume a high amount of recycled tyres accumulated in stockpiles.

There are different concerns regarding the introduction of rubber into concrete, which were addressed by previous studies. On the one hand, making a homogenous mix containing even distribution of rubber is a challenge. On the other hand, the severe reduction of concrete strength limits the rubber content. Moreover, replacing a portion of fine aggregates with low-stiffness rubber particles raises concerns regarding the generated shrinkage and cracking of rubberised concrete. This thesis investigates these concerns thoroughly and provides a comprehensive know-how of rubberised concrete characteristics, using crumb rubber.

In order to improve the strength of rubberised concrete different rubber treatment has been introduced by previous studies. A commonly applied rubber treatment method in the literature termed sodium hydroxide (NaOH) treatment has been assessed in this study. Numerous investigations examined using sodium hydroxide treatment of rubber. However, the level of improvement provided by different studies was not consistent. It was found that the sodium hydroxide treatment method is required to be optimised to achieve the most promising results. Two arrays of concrete specimens were prepared using different water cement ratios and a wide range of rubber contents. Then, the common fresh and hardened mechanical tests were conducted on the prepared samples. The results indicated that the duration of rubber treatment should be optimised based on concentration of the alkali solution and the type of recycled rubber. Consequently, the 24-hour treatment duration for crumb rubber resulted in the most suitable fresh and hardened concrete characteristics. Compared to untreated rubberised concrete, rubberised concrete produced with the optimised sodium hydroxide treated rubber, showed 25% and 5% higher compressive and flexural strength, respectively.

Based on a large number of tests, this research introduced a relationship between the strength of rubberised concrete and three key parameters including the water-cement ratio (WC), the concrete age and the rubber content. Using this relationship enables concrete producers to have an accurate estimate of rubberised concrete strength.

In addition, this research investigated the effects of applying an innovative method of rubber treatment, named “water-soaking”. Unlike the current methods of adding rubber into a concrete mix, which are conducted in a dry process, this research trialled introducing of rubber particles into the concrete mix in a wet process. Conducting the required sets of fresh and hardened concrete tests, number of mix series with a variety of rubber contents and water-cement ratios were evaluated. In order to measure the effectiveness of the introduced method, the properties of concrete containing water soaked rubber were compared with concrete containing untreated rubber. It was revealed that applying the proposed method resulted in considerable improvement of fresh and hardened properties. Applying the water-soaked method resulted in 22% higher compressive strength, and the formation of stronger bonds between rubber particles and cement paste compared to concrete made with untreated rubber.

The effects of using recycled tyre rubber on shrinkage properties of rubberised concrete were evaluated. It was observed that adding rubber into a concrete mix led to minimise shrinkage cracks, if only an optimised content of rubber was applied. Therefore, the optimised rubber content was determined based on the mix design properties, the early-age tensile strength, and the results of plastic and drying shrinkage tests. Accordingly, the early-age mechanical strength tests, toughness test, bleeding test, and the plastic and drying shrinkage tests were conducted. A semi-automated image processing method of crack analysis was introduced in this research. Average cracks width, length, and area were determined accurately by applying the introduced method. In addition, the experimental data resulted from drying shrinkage tests of rubberised concrete were crosschecked with the results of numerical shrinkage formula provided in the Australian Standard AS3600. It was found that the provided relationship in the Australian Standard AS3600 is a valid measure for estimating the drying shrinkage of rubberised concrete.

By considering the shrinkage characteristic and the acceptable mechanical performance of rubberised concrete, this dissertation concludes that the most promising results could be achieved for samples prepared with water-cement ratios of 0.45 and 0.40, and rubber contents of 20% and 25%, respectively.

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Finally, I wish to express my deep gratitude to my family for their support and encouragement.

LIST of Publications

During the course of this research, a number of publications have been made which are based on the work presented in this thesis. They are listed here for reference.

Mohammadi, I & Khabbaz, H 2013, "Challenges Associated with Optimisation of Blending, Mixing and Compaction Temperature for Asphalt Mixture Modified with Crumb Rubber Modifier (CRM)", Journal of Applied Mechanics and Materials, Vol. 256, pp. 1837-1844

Mohammadi, I, Khabbaz, H & Vessalas, K 2014, "In-depth assessment of Crumb Rubber Concrete (CRC) prepared by water-soaking treatment method for rigid pavements", Journal of Construction and Building Materials, Vol. 71, pp. 456-471

"Enhancing Mechanical Performance of Rubberised Concrete Pavements with Sodium Hydroxide Treatment" is submitted to the journal of "Materials and Structures (MAAS)"

"Shrinkage Performance of Crumb Rubber Concrete (CRC) Prepared by Water-Soaking Treatment Method for Rigid Pavements" is submitted to the journal of "Cement and Concrete Composites"

Table of Contents

List of Figures

List of Tables

List of Notations and Symbols

The symbols used in this report, including their definitions, are listed below:

Air Content	*AC*
Air Entraining Admixture	*AEA*
Gross Cross-Sectional Area of a Concrete Element	A_g
Untreated Rubber	*ARR*
Cement Concrete & Aggregates Australia	*CCAA*
Compacting Factor	*CF*
Crumb Rubber	*CR*
Crumb Rubber Concrete	*CRC*
Crack Reducing Ratio	*CRR*
Calcium Silicate Hydrate	*C-S-H*
Concrete Modulus of Elasticity	E_c
Characteristic Compressive Strength	f'_c
Characteristic Compressive Strength at 28 days	$f'_{c,28}$
Mean Compressive Strength of Concrete	f_{cm}
Mean Compressive Strength at Age of t	$f_{cm.t}$
Flexural Stress	f_{ctf}
Flexural Stress up to Net Deflection of L/150	$f^D_{T,150}$
Flexural Stress up to Net Deflection of L/600	$f^D_{T,600}$
Flexural Strength	f_P
Fibre Reinforced Concrete	*FRC*
Tensile Strength	f_t
Interfacial Transition Zone	*ITZ*
Linear Variable Differential Transducers	*LVDT*
Modulus of Elasticity	*MOE*
Modulus of Rupture	*MOR*
Mass per Unit Volume	*MPV*
Sodium Hydroxide	*NaOH*
Capillary Pressure	P_c
Peak Flexural Tensile Strength up to Net Deflection of L/150	P^D_{150}

Peak Flexural Tensile Strength up to Net Deflection of L/600	P^{D}_{600}
Peak Flexural Tensile Strength	P_P
Rubber Content	R
Radius of Menisci	r
Equivalent Flexural Strength Ratio up to a Net Deflection of L/150	$R^{D}_{T,150}$
Equivalent Flexural Strength Ratio up to a Net Deflection of L/600	$R^{D}_{T,600}$
Relative Humidity	RH
Styrene Butadiene Rubber	SBR
Specific Gravity	SG
Shrinkage Limited	SL
Stress Reduction Factor	SRF
Surface saturated Dry	SSD
Air Temperature	T_a
Concrete Temperature	T_c
Area Under the Load-Deflection Curve up to a Net Deflection of L/150	T^{D}_{150}
Area Under the Load-Deflection Curve up to a Net Deflection of L/600	T^{D}_{600}
Hypothetical Thickness of a Member	t_h
Exposed Perimeter of a Member	u_e
Water-Cement Ratio	WC
Water Reducer	WR
Surface Tension of Water	γ
Mid-Span Deflection	δ
Final Basic Drying Shrinkage Strain	ε^{*}_{csdb}
Final Autogenous Shrinkage	ε^{*}_{cse}
Shrinkage Strain of Concrete	ε_{cs}
Drying Shrinkage Strain	ε_{csd}
Chemical (autogenous) Shrinkage Strain	ε_{cse}
Shrinkage Strain	ε_s
Normal Compressive Stress	σ_{nom}
Tensile Stress	σ_t

Chapter 1

Introduction

1.1 Research Scope

1.2 Research Objectives, Significance and Innovations

1.3 Organisation and Thesis Layout

1.1 Research Scope

In many countries around the world, the adverse environmental impacts of stockpiling waste tyres have led to investigate alternative options for disposal of waste tyres. The disposal of waste tyres has been found to be an environmental concern due to waste tyres resisting degradation. Waste tyres occupy large landfill spaces that contain nesting insects and rats. Stockpiles of tyres destined for landfill are also known to be flammable. One option to reduce this environmental concern is for the construction industry to consume a high amount of recycled tyres accumulated in stockpiles. In Australia, the trend for accumulated waste tyres is rising at a rate of 2%, and it is estimated more than 20 million tyres were accumulated in landfills by the year 2010 (Atech Group 2001), which makes investigation into alternative options for disposing waste tyres a valid option. Moreover, according to a report prepared for the Australian Department of Environment only 3% of recycled tyres are used in civil engineering applications, which is far below the range of 9% to 14% average civil engineering usage of recycled rubber in other developed regions of the world, such as the United States and Europe (Houghton & Preski 2004). In addition, the Department of Environment in Australia emphasised the prospects for growth in using recycled crumb rubber, particularly in road construction applications (Atech Group 2001).

In order to reduce unnecessary landfills and preserve the environment, recycled tyres can feasibly be used as an alternative raw material in the construction industry (Pelisser et al. 2011). For example, in the pavement industry, trialling the use of crumb rubber has been initiated with asphalt mixes. However, some difficulties have been found that limit its application, such as the high viscosity of the rubberised bitumen and the higher temperature for production of rubberised asphalt (Mohammadi & Khabbaz 2012).

The first rubberised concrete was introduced and explored for potential engineering applications in the early 1990s (Kaloush et al. 2005; Allen 2004). Although combining recycled rubber and concrete aggregates for making conventional concrete was an innovative idea, it was found that the resulting rubberised concrete had lower strength (Khatib & Bayomy 1999; Sgobba et al. 2010a; Bewick et al. 2010; Ling et al. 2009; Khaloo et al. 2008), and this was not preferable especially for structural applications (Ho et al. 2009). However, rubberised concrete has been found to be preferable for paving applications, where lower range of strengths are including in design (John &

Kardos 2011; Ho et al. 2012). Consequently, the introduction of rubber to concrete pavements was the basis of this investigation.

Severe reduction of the concrete strength was reported as the main drawback of adding rubber into concrete (Khatib & Bayomy 1999; Zachar et al. 2010; Bewick et al. 2010; Ling et al. 2009; Khaloo et al. 2008). It was reported that a high content of rubber reduced as high as 90% of the compressive strength of rubberised concrete compared to control samples of concrete without rubber (Youssf & Elgawady 2013). Thus, it requires proper investigation on optimisation crumb rubber content in the concrete mix in order to achieve a rubber content, which increases the positive effects and lowers the negative impact of addition crumb rubber to the mix. Moreover, the systematic decrease in ultimate strength of crumb rubber concrete (CRC) might limit the use of it in concrete (Fattuhi & Clark 1996; Khaloo et al. 2008). Consequently, these negative impacts have led to using a variety of treatment methods to counteract the negative impact of adding rubber to concrete. Therefore, methods of treating rubber and optimisation of rubber content based on concrete mechanical properties were addressed in this research.

In concern with treating methods of crumb rubber two treatment methods were examined. Then, concrete properties prepared with treated rubber were compared to rubberised concrete prepared with untreated rubber. This assessment involved the study of commonly used sodium hydroxide treatment method and an innovative method of water-soaking treatment method. Afterwards, based on the concrete test results, the introduced water-soaking method was selected for preparing the main mix series of this study.

It can be stated that the incorporation of the rubber has two major opposite effects regarding mechanical characteristics of concrete. The negative impact is associated with the reduction of mechanical strengths. In contrast, the positive effect can be an increase of ductility and deformation capability. However, the extent of positive and negative effects are not similar for the different rubber contents (Kang & Jiang 2008). According to the literature, size of rubber particles significantly affects the properties of rubberised concrete (Sukontasukkul & Tiamlom 2012). In order to minimise the negative effect of adding rubber into the concrete mix, crumb rubber in the particle size range of one to four millimetres was selected for this study. It would be easier to consider usage of crumb rubber on a wider scale for its practical applications and disposal problem

(Rangaraju 2012). Thus, a variety of rubber content up to 70% and a broad range of water-cement ratios from 0.35 to 0.55 were examined for preparing concrete mix series.

After trialling different mix series, valid ranges for water-cement ratios and rubber contents were determined. The scope of this research is set to investigate the replacement of fine aggregates with crumb rubber in pavement concrete. In order to prepare the main mix series for pavement applications, it was found that the rubber content should be limited up to 40% and the water-cement ratio is required to be set in the range of 0.40 to 0.45. Afterwards, the effects of the crumb rubber inclusion were assessed by comparing mixes to a control mix without rubber. Moreover, strength properties of rubberised concrete studied in depth and an appropriate relationship for estimating the strength of CRC was formulated and introduced.

Finally, the effects of using rubber on shrinkage properties of CRC were studied. The time-dependent strain development and cracking characteristics were evaluated. Although the assessment of generic properties for CRC is the requirement of Australian concrete pavement standard, this research was not limited to them. Plastic and drying shrinkage of rubberised concrete was studied and based on the results arose from all tests rubber content was optimised for each array of concrete samples.

1.2 Research Objectives, Significance and Innovations

1.2.1 Objectives

Although much research has been conducted thus far on the concept of using recycled rubber in cementitious composites, very limited studies have been performed on the application of crumb rubber concrete (CRC) for pavements. The term of rubberised concrete is a general term, which involves all types and sizes of recycled rubber. The aim of this research is to extend the knowledge of crumb rubber concrete characteristics used for the pavement application. In this investigation, the conducted tests not only embraced the mechanical and shrinkage properties of rubberised concrete, but also extended to rubber treatment methods. In addition, methods of introducing rubber were examined. The major objectives of this research can be summarised as follows:

a) Providing the required information regarding the use of crumb rubber for concrete pavements and integrating the past and existing studies about rubberised concrete.

b) Quantifying the general mechanical properties of crumb rubber concrete through systematic laboratory tests. In addition, some theoretical studies are performed to provide a deep understanding of effects of adding rubber as a low stiffness material in the concrete matrix. The possible advantages and disadvantage of introducing different volumes of crumb rubber into the concrete mix are evaluated.

c) Establishing an experimental relationship for predicting the strength properties of CRC by considering the effects of different variables, such as the concrete age, the rubber content and the water-cement ratio.

d) Investigating the possibility of adding recycled rubber into the concrete mix in order to improve shrinkage properties and crack-resistance of concrete.

e) Conducting an in-depth investigation regarding the advantages of treating rubber before adding into the concrete mix, which includes trialling an innovative treatment method termed “water-soaking”.

f) Investigating the effect of the sodium hydroxide (NaOH) treatment of crumb rubber on rubberised concrete properties, in order to optimise this method.

1.2.2 Significance

Previous studies in the field of rubberised concrete reviewed and some difficulties associated with the production of rubberised concrete were highlighted. This investigation intends to address these difficulties and provides some solutions to mitigate them. The following points elaborate the significance of this research:

a) Study the challenges associated with the production of concrete mix with crumb rubber and introduction of methods to mitigate the challenges. Those challenges cause difficulties and inaccuracy in the determination of proper content of rubber in the mix, determining the specific gravity of crumb rubber accurately, finding the best method of adding rubber into the mix, and problems regarding vibration and compaction of crumb rubber concrete.

b) Maximise the application of rubber in pavement mixes the environmental problems associated with stockpiling of waste tyres can be mitigated. In addition, replacing a portion of natural aggregates with recycled rubber tyres saves the Australian natural aggregate resources, also serves sustainability of concrete production in the future.

c) Satisfy the Australian Standards and the New South Wales Authorities guidelines for preparing concrete used in pavement applications. The Australian Standards are followed in all procedures such as making and testing concrete. Moreover, local typical cement, sand and coarse aggregates, also local recycled waste tyre were used for all test series.

d) The previous conducted studies on CRC were focused on the effect of changing of rubber content as a variable in the concrete mix. However, this research examined a broad range of rubber content and water-cement ratios, in order to provide a deep understanding of rubberised concrete properties. Unlike the other investigations in the field of rubberised concrete, this research assessed various sets of rubberised concrete with multiple variables to develop the understanding of the impacts of different variables, such as rubber content, sand content, WC ratio and concrete age on concrete properties.

e) The outcomes of this research may assist in drafting the first concrete specifications for crumb rubber concrete in Australia in the future.

1.2.3 Innovations

The innovations and original contributions of this research are listed below:

a) Application of the wet procedure for mixing rubber into the concrete mix was examined for the first time. It includes the introduction of an innovative rubber treatment method termed as “water-soaking” treatment. The improved mechanical characteristics of rubberised concrete have been assessed, by applying this method.

b) Investigating the crumb rubber treatment by sodium hydroxide solution. The duration of treating crumb rubber in the alkali solution has been optimised, based on the mechanical properties of treated rubberised concrete.

c) Introducing a relationship in order to estimate the strength of rubberised concrete based on influencing factors comprising the WC ratio, concrete age and rubber content. This relationship can assist practicing engineers to select the concrete constituents properly to achieve a specific grade of strength.

d) Only a limited number of studies are available, concerning the plastic shrinkage and cracking of concrete containing rubber particles. This investigation covers the possible preventive measures to reduce the effects of crumb rubber on shrinkage cracking of concrete. In order to assess the restrained plastic shrinkage, a sophisticated computer program has been designed. The designed semi-automatic procedure could accurately analyse the plastic shrinkage crack patterns, including the average cracks width, length and the area.

1.3 Organisation and Thesis Layout

This study is a comprehensive review of crumb rubber concrete, which has provided information regarding rubberised concrete used for pavement applications. This involves information regarding treating rubber before adding into the mix, the method of mixing rubber into concrete, introducing the concrete pavements testing procedures, analysing of the tests results, and finally drawing conclusions based on the results obtained. All these tests have been conducted in order to find the optimum content of rubber in the concrete mix. The thesis is divided into five chapters.

Chapter 1 outlines the definition of the problem and discusses the significance and innovations of this research. Moreover, the research scope and the brief review of thesis work flow are provided in this chapter.

Chapter 2 provides a thorough review of the mechanical and shrinkage properties of rubberised concrete based on the results of the previous investigations. The difficulties of working with rubberised concrete and research gaps are addressed in this chapter.

Chapter 3 is dedicated to describing the experimental program and set up. It involves the introduction of different constituents of rubberised concrete and other materials utilised for this research, as well as the testing methods used for evaluating different properties of rubberised concrete. Moreover, the Australian pavement design criteria, used for assessment of the test results are introduced. Lastly, properties of the different mix series prepared for the experimental stage are indicated in this chapter.

Chapter 4 demonstrates and compares the experimental results. Firstly, valid ranges for different variables involved in this research are investigated. Consequently, the proper ranges for water-cement ratio, rubber content and water reducer (WR) admixture are inspected. After setting the valid testing ranges, different treating methods of rubber examined and the "water-soaking" method was selected as the optimum treatment method. Then, arrays of samples were prepared for assessing the mechanical and shrinkage properties of concrete. Lastly, the change of concrete properties based on the change of different variables are indicated and discussed.

The main findings of this study are summarised in Chapter 5. Based on the achieved results, the optimum content of rubber in the concrete mix has been determined. Moreover, many recommendations are provided regarding the different methods of rubber treatment, procedure of mixing rubber into concrete and the performance of crumb rubber concrete. Finally, some recommendations for conducting future studies in the field of rubberised concrete are provided.

Chapter 2

Literature Review

2.1 Application of Recycled Rubber in Concrete Pavements

2.2 Physical and Mechanical Properties of Rubberised Concrete

2.3 Shrinkage Properties of Rubberised Concrete

2.1 Application of Recycled Rubber in Concrete Pavements

In this section, different characteristics of crumb rubber concrete (CRC) are investigated broadly. Based on the available research data, the function of rubber particles in the concrete matrix is critically reviewed. Moreover, different categories of recycled rubber and their effects on properties of concrete are elaborated.

The reduction in compressive strength of concrete manufactured with rubber aggregates limits its use in most applications (Khatib & Bayomy 1999; Zachar et al. 2010; Bewick et al. 2010; Ling et al. 2009; Khaloo et al. 2008). However, rubberised concrete has possibly some desirable characteristics such as lower density (Khaloo et al. 2008; Khatib & Bayomy 1999) and higher toughness and ductility (Topcu 1997; Zheng et al. 2008). Moreover, the better sound insulation, fire resistance (Bewick et al. 2010; Sukontasukkul 2009; Rangaraju et al. 2012) and resistance against cracking (Topcu 1995; Eldin & Senouci 1994) make rubberised concrete a preferred option to be used for pavement applications.

Concrete is a quasi-brittle material irrespective of whether rubber aggregate is used in the mix design. However, introducing rubber into the concrete mix can shift its mechanical properties from being a more brittle material to a more ductile one, especially when a high volume of rubber added into the concrete mix (Eldin & Senouci 1994). This performance is mainly due to the elastic properties of recycled rubber particles in the concrete matrix. The less brittle properties of crumb rubber concrete can be advantageous for various construction applications, such as driveways and roadway applications (Siddique & Naik 2004; Bewick et al. 2010). Many attempts were made to use rubber as a replacement for either coarse aggregates or fine aggregates in concrete mixes. The previous findings have revealed that the properties of rubberised concrete were critically affected by the type, size, and content of added rubber. According to Khaloo et al. (2008), the procedure of treating and introducing rubber into concrete mixes was also found to be significantly influential.

The main sources of recycled tyres are listed as the bike tyres, passenger car tyres and truck tyres (Atech Group 2001). The breakdown by use of tyres is demonstrated in Figure 2.1.

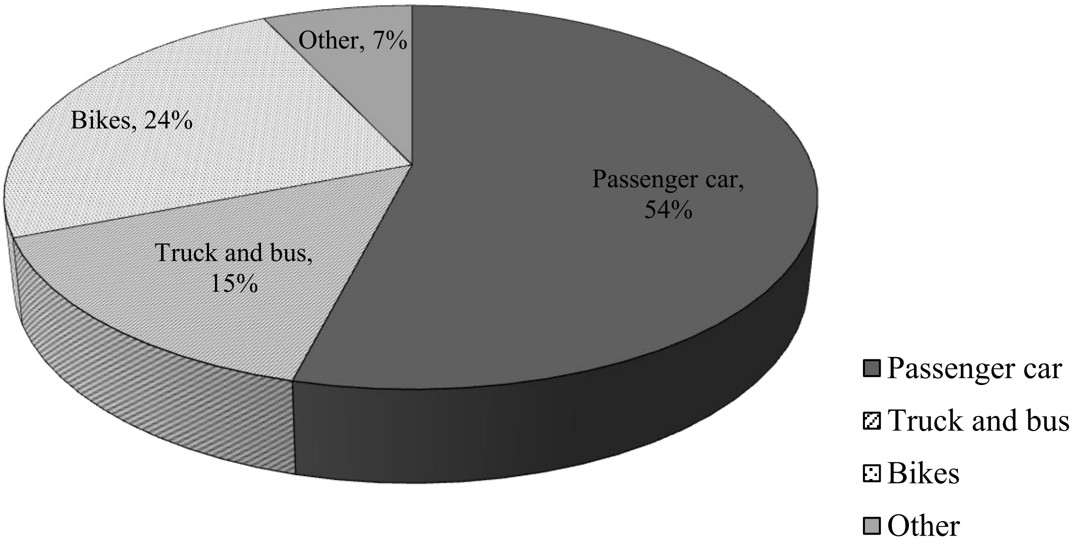


Figure 2.1: Estimated breakdown of the number of waste tyres (Atech Group 2001)

Although the source of rubber particles is a key factor (Zachar et al. 2010), the most important characteristic of recycled rubbers is the rubber particle size. Recycled rubbers can be classified into three main size categories (Figure 2.2) as follows:

a) Chipped or shredded rubber (coarse size rubber): Literature has classified recycled rubber as shredded or chipped rubber, when it has a dimension of about 4.75mm or larger. Accordingly, coarse aggregates in the concrete mix can be replaced with this size of rubber (John & Kardos 2011).

b) Crumb rubber (fine size rubber): Rubber particles are highly irregular, which can be used instead of a part of sand in the concrete mix. Crumb rubber particles are in the size ranges between 4.75mm and 0.075mm (Siddique & Naik 2004; John & Kardos 2011).

c) Ash rubber (rubber powder): Rubber consists of particles smaller than 0.075mm is named ash rubber or rubber powder. It is not prepared from rubber by grinding, but the powder is formed unintentionally during the trituration process, fallen from the machinery of the plant handling the waste rubber. It can be used as filler in concrete or be substituted as a portion of cement (Zachar et al. 2010).

Due to the production cost of ash rubber in concrete, the use of rubber powder is not a common practice in the construction industry (John & Kardos 2011). A summary of different sizes for rubber particles is presented in Table 2.1. Other types of recycled tyre rubbers, which are larger in size (>300 mm) such as chopped tyre or rough shred (Khaloo et al. 2008) are also available, but the application of these sizes in cementitious products was found to be very limited.

Table 2.1: Typical properties of recycled rubber commonly used in engineering products

Recycled Rubber Type	Average Particle Size [mm]	Specific Gravity [unitless]	Reference
Ash rubber	<0.075	0.95-2.20	(Zachar et al. 2010; Al-Akhras & Smadi 2004)
Crumb rubber	0.075 to 4.75	0.60-1.20	(Li et al. 1998; Richardson et al. 2002; Kaloush et al. 2005; Emira & Bajaba 2012)
Chipped rubber	>4.75	1.12 -1.16	(John & Kardos 2011; Taha et al. 2009; Fattuhi & Clark 1996; Siddique & Naik 2004)

As can be seen from Table 2.1 the presented specific gravity values were not same for different types of recycled rubber. Possible reasons were given for the variation in specific gravities of recycle rubber. The source of this variety could be due to the quality of rubber (Fattuhi & Clark 1996). Besides, some recycled rubbers may contain pieces of metal wire, which causes an increase in the specific gravity value. The difference between the specific gravity of recycled rubber and concrete aggregates is addressed as source of difficulty in mixing and compaction of rubberised concrete mix (Ho et al. 2009).

Figure 2.2: Main types of recycled rubber used in cementitious products (a) chipped rubber, (b) crumb rubber and (c) ash rubber

Recycled Rubber aggregates are produced in two different technologies. The first one is called "mechanical ambient grinding," which is conducted at the ambient temperature. In contrast, the second procedure, which is termed "cryogenic grinding," is carried out at a temperature below the glass transition temperature (Pacheco-Torgal et al. 2012). The ambient grinding technology has been used more commonly in waste tyre recycling industry in the recent years. The reason behind this was changes in energy costs, which altered the economic priority of this technology. Besides, the development of equipment that permitted grinding of whole tyres was significantly influential. Moreover, the additional benefit of applying the ambient technology is the separation and recycling of tyre steel content (Houghton & Preski 2004).

In this research crumb rubber in the size of 0.075 to 4.75 mm, which was sourced from recycled tyre was used. In addition, rubber used as the concrete modifier in this study was produced in an ambient recycling waste tyre plant. Accordingly, for this investigation the used recycled rubber was passenger car tyre, which represented the majority of waste tyre and was produced with the most common method of ambient grinding. More details regarding the used tyre are discussed in Section 3.1.3.

2.2 Physical and Mechanical Properties of Rubberised Concrete

According to the Austroad standard, the compressive and flexural strength are two major criteria, which are required to be assessed for concrete pavements (Austroad 2009; RTA R83 2010). Literature reported that the replacement of the volume of the coarse or fine aggregates with rubber resulted in the reduction both of the compressive and flexural strengths. In the same trend, the reduction in strength was accompanied by an increase in the air content. Moreover, workability of rubberised concrete was measured lower than concrete prepared with the same constituents but without rubber.

The results of the previous studies indicated the significant effect of adding rubber into the concrete mix. As a consequence, selection of any rubber content in a pavement mix should be conducted by considering the requirements of the pavement specifications, which are addressed by Australian pavement standard (Austroad 2009; RTA R83 2010). Consequently, satisfying the principal criteria regarding the mechanical strength is set as the main intention of optimising rubber content in the concrete mix. Besides, achieving the possible performance benefits, such as improvement in the occurrence of shrinkage cracking, fatigue behaviour and higher fracture resistance, are highly preferable.

2.2.1 Fresh Properties of Crumb Rubber Concrete Pavement

A proper concrete in the fresh state can be defined based on two major requirements. Firstly, it should be plastic or semifluid and secondly, it should have enough workability to be pumped and/or moulded by hand (Mehta et al. 2006). Workability and compactability properties of concrete mixes are key characteristics of fresh concrete. Pavement concrete needs to have a certain level of these characteristics in order to remain cohesive and not segregated under the applied external effort. A very wet and fluid concrete may cast into the shape well, but it may not be defined as a satisfactory concrete if it is not cohesive enough, and becomes segregated easily (Mehta et al. 2006). It should be taken into account that because of the large difference between the unit weight of rubber and other concrete constituent, rubber particles can be segregated from the concrete mix during production, casting and compaction. Therefore, adding the low unit weight crumb rubber particles into concrete mixes makes them more sensitive to the casting and compaction.

A workable pavement concrete keeps homogeneity during handling and placement, which resulted in production and casting of that without struggling. This concrete is strong enough (with sufficient cohesiveness) to be fluid without being separated out. Workability can also be defined as the degree of resistance to segregation, which means ingredients should not separate during transportation and handling. Major factors affecting workability are summarised in Table 2.2:

Table 2.2: List of the factors affecting the workability of concrete mix (Mehta et al. 2006; Neville & Brooks 2010)

Increase in	Results in
Content of free water in concrete mix	Increase of workability
Content of cement and cementitious materials	Increase of workability
Content of Admixtures	Increase of workability
Grading degree of aggregates	Increase of workability
Harshness of aggregates	Decrease of workability

There are different qualitative and quantitative tests methods available for measuring the plasticity and workability of concrete, when it is in the fresh state. In this study, three principal methods were used for qualitative and quantitative measurement of workability, which can be listed as visual inspection, measuring the slump number and conducting the compacting factor test.

From the one hand, visual inspection should be applied to all mix sets to assess the homogenousity of incorporated rubber into the mix. From the other hand, the purpose of a slump test is to determine the consistency of fresh concrete, and to check the workability and uniformity of mix series. Besides, the compacting factor test can be performed as a complimentary test, which the result of this test is a good indicator of the stability condition of the produced concrete pavement. Concrete with compacting factor (CF) values of less than 0.70 or higher than 0.98, are classified as unsuitable concrete (BS1881-103 1993). There are other complementary tests available for fresh concrete such as air content (AC) test and mass per unit volume (MPV) test, which were performed in this study. Fresh properties of concrete are dependent on both the raw material characteristics and combination of them in the concrete mix. Literature indicated that fresh properties of concrete mix were subjected to change by using rubber particles in the concrete mix. The effects of introducing a variety of rubber content on the fresh properties were investigated thoroughly in the literature and are discussed in the following sections.

Slump

Literature shows that introducing rubber into the concrete mix reduces its workability (Rangaraju et al. 2012; John & Kardos 2011; Khaloo et al. 2008; Siddique & Naik 2004; Sukontasukkul 2009; Khatib & Bayomy 1999; Taha et al. 2009), but there is not a consensus on the degree of slump reduction among studies. Rubber particles tend to entrap air in the concrete mix. Traditional concrete trialling has revealed more air in the prepared mix, up to 9%, results in more workable concrete; however, this trend, which holds true for traditional concrete mix, cannot be applied to rubberised concrete mix (John & Kardos 2011)

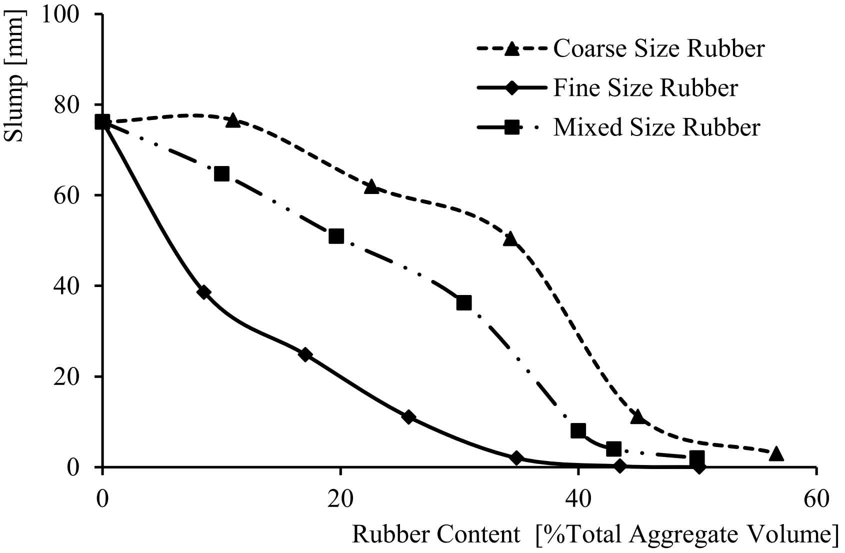


Figure 2.3: Effect of rubber content and rubber particle size on the slump value (after Khatib & Bayomy 1999)

The effects of mix constituents on slump number have been studied by many researchers. Figure 2.3, depicts the effect of different rubber particle sizes on the level of slump reduction. However, for all the rubber sizes (fine, mixed and coarse) the overall trend of slump reduction at higher rubber contents is similar (Taha et al. 2009; Khatib & Bayomy 1999). The results of the investigation conducted by Taha et al. (2009) indicated that adding larger rubber particles resulted in less reduction of the slump number. In contrast, Khatib & Bayomy (1999) reported the stronger effect of coarse rubber size on slump reduction.

Moreover, it can be inferred from Figure 2.4 that a change in mix water to cement ratio had not a significant effect on the trend of slump loss.

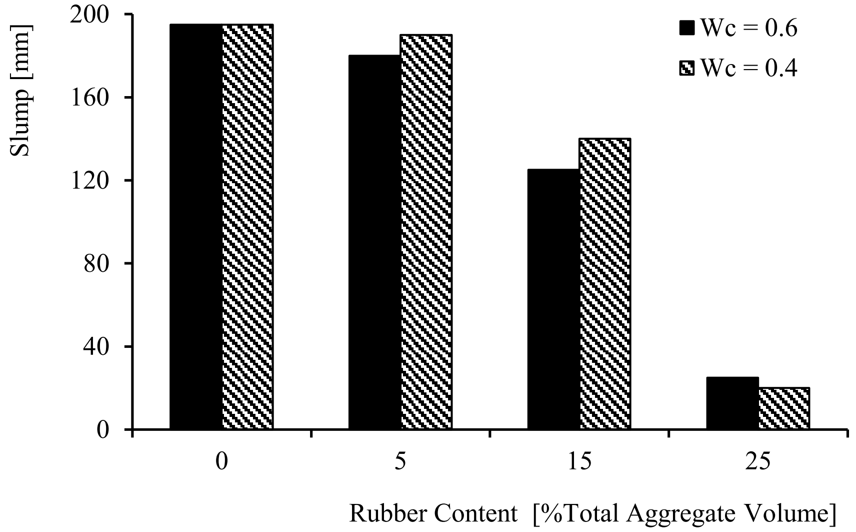


Figure 2.4: Effect of rubber content and water-cement ratio on slump value (after Gesoglu & Guneyisi 2007)

It is indicated by most studies that the slump number was reduced by addition of crumb rubber into the concrete mix. In this investigation, it is intended to keep the slump number at the value of 60±10 mm according to the required Australian road construction specifications (Austroad 2009; RTA R83 2010). The review of Literature shows that the target slump can be achieved if appropriate concrete admixture is used. For instance, in the study carried out by (Ho et al. 2009) the slump number was adjusted to the value of 100±20 mm by adjusting the content of super-plasticiser.

Air Content

The air content (AC) is another criterion, which should be assessed for concrete pavements according to the Austroad pavement standards. An unexpected increase in the air content has negative impacts on the compressive and flexural strengths, and also the durability of concrete pavements. Any 5% of void in the concrete mix can reduce the compressive strength up to 30%. Even 2% of void can result in a drop of the strength more than 10%. On the other hand, it would be beneficial to keep air content around 4%, as it has a positive effect on durability of concrete in terms of freeze-thaw resistance (Neville & Brooks 2010). An increase in the volume of air, results in a lower mass per unit volume (MPV) when all other concrete constituents are kept constant.

The air content test measures the total air content of concrete mix; however, it cannot differentiate between entrapped and entrained air content in the mix. Based on the definition, the entrapped and entrained air content terms are often applied to distinguish between large and small air voids, respectively. Literature revealed rubberised concrete had higher air content (Khaloo et al. 2008; Siddique & Naik 2004). In a study conducted by Youssf & Elgawady (2013), the prepared rubberised mix had an air content of approximately 2.4–3.3% compared with 1% air content of the control mix without rubber. Moreover, it was reported that the measured AC values were placed in the range of 0.5% to 5.5% for mixes containing 8% to 24% of rubber particles by volume of fine aggregates (Rangaraju et al. 2012). It was noted that AC would stay in the range of 1% to 4% for any replacement of aggregates with rubber up to 50% of total aggregate content (Khatib & Bayomy 1999). Research carried out by John & Kardos (2011) presented 2% to 5.6% AC for the mix containing rubber 20% to 40% of the volume of fine aggregates, while Li et al. (2004) illustrated 4% to 5% of AC for rubberised mix, which prepared by replacing 15% of coarse aggregates with chip rubber. Another research reported that the replacement of aggregates by rubber in the range of up to 100% resulted in increasing of air content from 1% to 7.5% for both of the fine and course aggregates replacement (Taha et al. 2009).

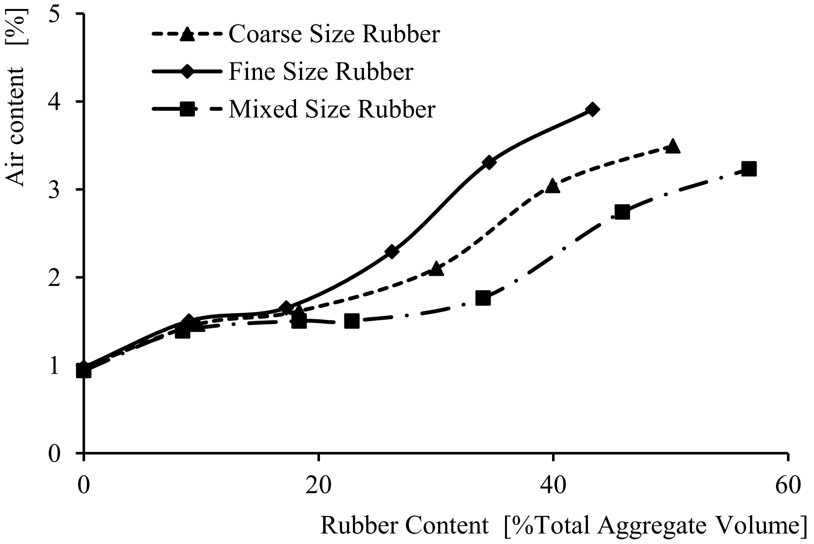


Figure 2.5: Effect of rubber content and rubber particle size on the air content (Khatib & Bayomy 1999)

It has been reported that the rubber particle size can affect the AC of concrete mixes. Replacement of fine aggregates by rubber particles resulted in less increase of air content compared to the condition that coarse aggregates were replaced by crumb rubber (Youssf & Elgawady 2013). In contrast, it was noted by Khatib & Bayomy (1999) that the rubber particles, which were coarser, resulted in a less increase in AC compared to the finer size of rubber particles (Figure 2.5). It was denoted that the growing trend for the air content value held true for all sizes of rubber particles (Taha et al. 2009; Khatib & Bayomy 1999). By increase of rubber content the entrapped air in the mix inclined; however, it was revealed that the entrapped air could be substantially reduced by adding a de-airing agent into the concrete mix (Kaloush et al. 2005).

It can be concluded from the literature that addition of rubber increases the entrapped air content. The air content should be controlled and limited in the concrete pavements, since it is reported that air content of over 9% can result in durability problems (Zhang & Wang 2005); Moreover, it has a negative impact on the compressive strength of pavement concrete (Neville 2011). In this research, it is intended to limit the air content to the value of 6% according to the requirements of the Australian pavement specifications (Austroad 2009; RTA R83 2010).

Mass per Unit Volume

Crumb rubber is a lightweight aggregate, and its addition to pavement concrete, reduces the unit weight of concrete (Emira & Bajaba 2012). Pavement concrete with 28-day compressive strength of 32MPa typically does not classify as non-structural lightweight concrete. literature reported that density of concrete is reduced by introducing rubber into the mix (Siddique et al. 2008; Sukontasukkul 2009; Rangaraju et al. 2012; John & Kardos 2011; Youssf & Elgawady 2013; Fattuhi & Clark 1996), because the density of rubber is much lower than the density of other concrete constituents (Fattuhi & Clark 1996; Sgobba et al. 2010).

By replacing conventional fine aggregates with crumb rubber at 5% to 30% (based on the volume of fine aggregates), the unit-weight of concrete was reduced from 14% to 28% depending on the crumb rubber type and content (Sukontasukkul 2009; Rangaraju et al. 2012). John & Kardos (2011) reported that by replacing 8% to 24% (based on the volume of fine aggregates) the unit weight of concrete was reduced continuously in the range of 6% to 15% as compared to the control concrete samples.

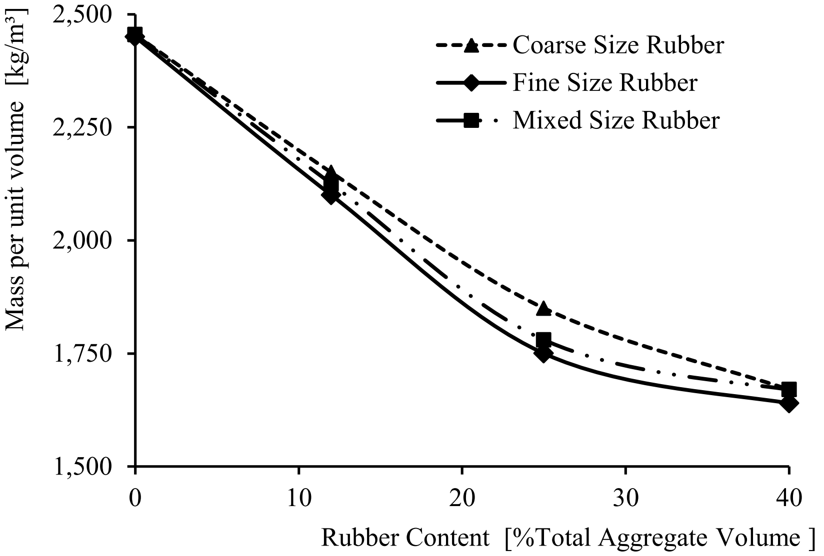


Figure 2.6: Effect of rubber content and rubber particle size on the MPV (after Khaloo et al. 2008)

The effect of rubber size on the concrete unit weight was studied in detail by a number of researchers. It was noted that there is no significant difference between the MPV values of rubberised mixes based on the rubber particle size or water-cement ratio (Emira & Bajaba 2012; Khatib & Bayomy 1999; Gesoglu & Guneyisi 2007).

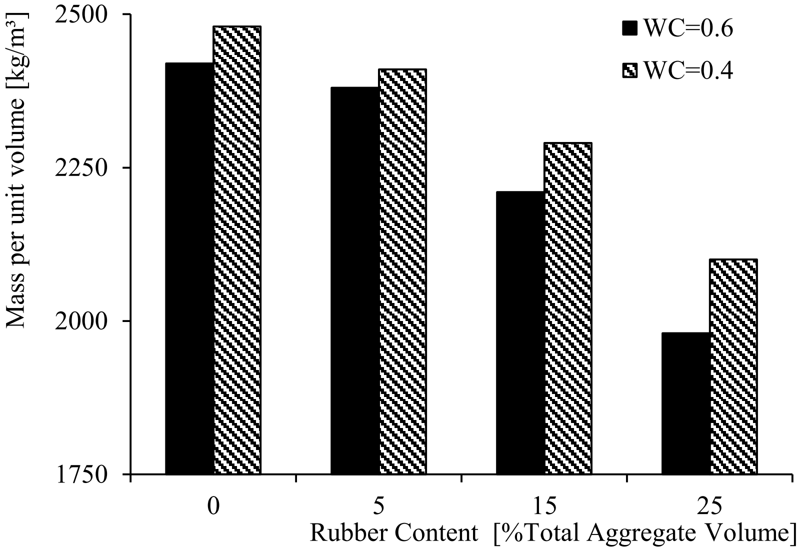


Figure 2.7: Mass per unit volume of rubberised mixes with different water-cement ratios and rubber content (after Gesoglu & Guneyisi 2007)

It was reported that replacing 21% of fine aggregates by crumb rubber, the unit weight decreases by approximately 26% (Youssf & Elgawady 2013). John & Kardos (2011) pointed out when 33% by volume of sand was replaced in a mix with crumb rubber the unit weight was reduced by approximately 10%. Another research reported the density of the concretes containing rubber rely on the rubber content and can be placed in the range between 1880 and 2380 kg/m³ (Fattuhi & Clark 1996; John & Kardos 2011).

It has been found the unit weight of CRC decreases approximately 100 kg/m³ for every 25 kg of rubber added to the mix (Kaloush et al. 2005). Another research performed by Khaloo et al. (2008) showed that the major factor, which influenced the decrease of MPV, was rubber content (Khatib & Bayomy 1999; Khaloo et al. 2008; Zheng et al. 2008). Other factors such as the rubber size (Figure 2.6), the ratio of water to cement in mix design (Figure 2.7) did not affect mass per unit volume as significantly as the rubber content.

2.2.2 Hardened Properties of Crumb Rubber Concrete Pavement

Generic mechanical properties of pavement concrete are dependent on the concrete constituent materials and also the concrete production procedure. The majority of the previous studies discussed hardened properties of rubberised concrete were laboratory based experimental work. Accordingly, the key finding regarding introduction of rubber into the concrete mix was that the produced rubberised concrete suffered a reduction in the strength (Tian et al. 2011; Zheng et al. 2008; Kaloush et al. 2005; Weiss et al. 2000; Xi et al. 2004; Khatib & Bayomy 1999). The detailed effects of introducing rubber on the hardened properties of rubberised concrete were investigated thoroughly in the literature and are discussed in the following sections.

Compressive Strength

The compressive strength is the most important index of pavement concrete and is widely used as an index of the concrete strength. Although the main stress that rigid pavements undergo is tensile flexural stress, the most common strength test is carried out in pavement concrete industry is compressive strength tests. Many studies showed that there was an extensive reduction in hardened properties (both compressive and flexural strengths) of crumb rubber concrete (CRC) when the volume of rubber used in the mix was more than 5% of the total volume of mix (Tian et al. 2011; Shengxia et al. 2006; Khorrami et al. 2010). In addition, it was observed that the larger amount of added rubber results in higher decrease of strength. Therefore, from a practical viewpoint, the rubber content should not exceed 20% of the total volume of mix aggregates due to the severe negative impact it has on concrete strength (Khatib & Bayomy 1999). It was estimated by another study that when the content of rubber was in the range of 2% to 4%, every excess 1% volume of rubber content reduced the strength by 4% to 8%, which illustrated the severe negative effect of rubber on concrete strength (Shengxia et al. 2006). There is a strong correlation between the increase of rubber content and the loss in concrete compressive strength at 28 days (Figure 2.8).

$$\text{Compressive Strength Loss}\,[\%] = 1 - \frac{CSR}{CSC} \tag{2.1}$$

where *CSR* is the compressive strength of the rubberised samples in MPa and *CSC* is the compressive strength of the control samples in MPa.

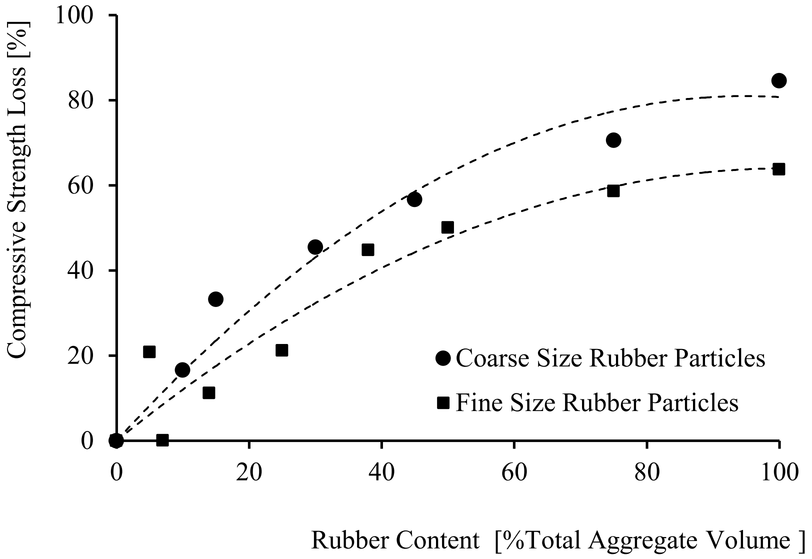


Figure 2.8: Effect of rubber content and rubber particle size on the compressive strength (Youssf & Elgawady 2013)

There are different reasons given for lower strength of rubberised concrete:

a) The difference between elastic modulus of concrete aggregates and rubber is significantly high (Youssf & Elgawady 2013). Consequently, the low stiff rubber particles do not carry the load in the concrete matrix. This effect of rubber was termed “reduction in the effective surface of concrete” (Eldin & Senouci 1994).

b) The weak adhesion of rubber particles and cement paste results in the formation of weak Interfacial Transition Zone (ITZ) between rubber and cement paste (Li et al. 2010). The formation of weak bond reduces both flexural and compressive strengths of pavement concrete. Besides, the large deformability of rubber, leads to the high stress concentrations around the rubber particles, leading to early failure of rubberised concrete samples under the applied load.

c) The sand content of concrete mix plays an important role in concrete strength (Neville & Brooks 2010). Therefore, replacement of the sand content with crumb rubber possibly results in the formation of a weaker matrix, which leads to lower compressive strength.

d) The non-homogenous distribution of rubber particles in the concrete matrix, results in the reduction of the concrete strength (Ho et al. 2009). Rubber has a specific gravity lower than concrete constituent elements. In addition, over-vibration of the rubberised mix, results in migration of crumb rubber particles to the top surface of concrete.

e) Rubber particles have a hydrophobic (water repelling) nature, when they are mixed with water (Richardson et al. 2011; Youssf & Elgawady 2013; Taha et al. 2009; Siddique & Naik 2004). This behaviour of rubber particles entraps air bubbles, which are attached to them and then takes the bubbles into the concrete mix. It is reported that the addition of rubber particles to the concrete mix increases the air content of the mix (Khaloo et al. 2008; Siddique & Naik 2004). A major result of the increase in the air content is reduction in the concrete strength (Neville & Brooks 2010; Mehta et al. 2006).

f) The next reason, which is elaborated by this research in detail, is associated with the effect of rubber concentration in the concrete matrix. The high concentration of rubber in the concrete mix, results in the formation of the rubber to rubber connections. Unlike aggregate to aggregate connections, the rubber to rubber connections cannot transfer load stress at the same level. It can results in early failure of rubberised samples, prepared with a high concentration of rubber (Mohammadi et al. 2014).

Modulus of Rupture

Tensile strength is a critical characteristic of pavement concrete and prevents serious cracking. It is a proper means of strength evaluation especially for designing thickness of pavements and other slabs (Austroad 2009). However, the direct tensile tests of concrete are seldom carried out, mainly because the specimen holding device introduces secondary stresses that cannot be ignored (Mehta et al. 2006). The 28-day flexural strength is a key design parameter in pavement performance, which is used in the determination of base concrete thickness. Thus, it is selected for assessment of crumb rubber concrete pavement in this investigation. As can be seen from Figure 2.9, a decrease in the Modulus of Rupture (MOR) was reported as content of rubber was increased (Li et al. 2011; Ganjian et al. 2009; Khorrami et al. 2010). It was expected as the compressive strength decreases with an increase in rubber content. Moreover, addition of rubber results in higher flexural deformation (Li et al. 2011) and flexural strain of rubberised samples (Kang & Jiang 2008).

Presence of rubber particles is expected to act as a hole at flexural cracks tips; therefore, the tip sharpness of cracks decreases by rubber particles. It has been indicated that the cracks can be prevented from propagation, by slowing down the kinetics of the first crack's propagation (Ho et al. 2009). Tyre rubber as a soft material, acts as a barrier against the crack growth in concrete (Khorrami et al. 2010). It has also been observed that the ability of flexural deformation of the specimens can be improved, while the flexural elastic modulus reduces significantly (Li et al. 2011).

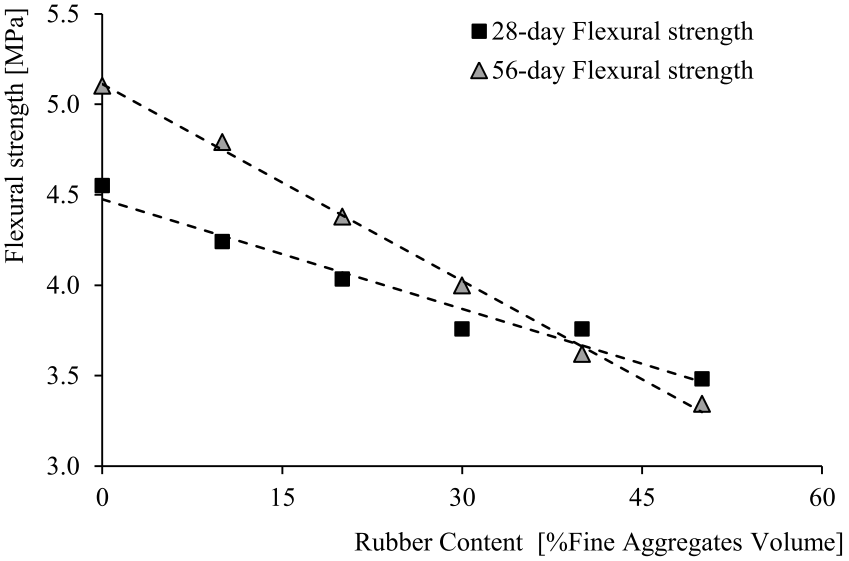


Figure 2.9: Effect of rubber content on flexural strength at different testing ages (after John & Kardos 2011)

The ratio of the flexural strength to the compressive strength (f_{ctm}/f_{cm}) is another influential index, the greater of the ratio in the concrete, the stronger resistance against the tensile crack (Kang & Jiang 2008). Literature showed that, introduction of rubber had more negative impact on the compressive strength than that on the flexural strength of rubberised concrete (Khorrami et al. 2010; Ganjian et al. 2009). Moreover, it has been reported that a significant increase in ultimate strain can be achieved by rubberised concrete. The ultimate strain and deflection increases four times by the use of rubber content of 20% of the total aggregate volume (Kang & Jiang 2008).

Modulus of Elasticity

The modulus of elasticity is a key property of pavement concrete since it impacts the serviceability and performance of pavement (Zheng e al. 2008). The elastic modulus of concrete is closely related to the property of the cement paste and stiffness of mix selected aggregates (Topcu 1995). Concrete aggregates have elastic modulus of 50 GPa while the elastic modulus for crumb rubber is placed in the range of 0.001 to 0.01 GPa. As a consequence, rubberised concrete has lower elastic modulus than plain concrete (Khaloo et al. 2008; Kaloush et al. 2005). It is denoted that MOE decreases with the increase in the rubber content as shown in Figure 2.10 (John & Kardos 2011; Zheng et al. 2008).

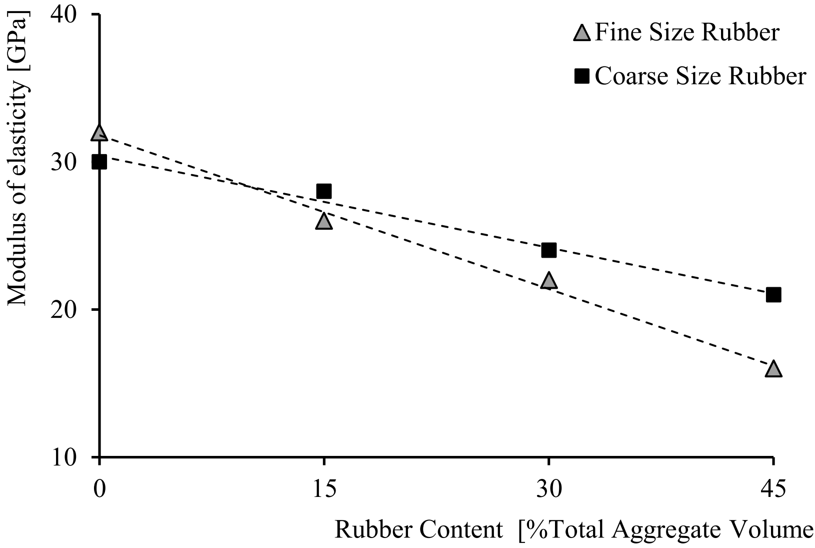


Figure 2.10: Effect of rubber content and size on the modulus of elasticity (after Ho et al. 2009)

By increasing rubber to 20% of the mix aggregate content, the static MOE is expected to decrease approximately 30% (Youssf & Elgawady 2013). The decrease of MOE for rubberised concrete can be logically justified by the well-established fact that the MOE depends on the modulus of elasticity and the volumetric proportion of concrete constituents (Ho et al. 2009). This reduction in MOE is an advantage of rubber modification for pavement concrete. The higher ductility compensating the reduction of rigidity due to rubber aggregates (Ho et al. 2009). The lower value for MOE in rubberised concrete results in lower sensibility of rubberised concrete to thermal or shrinkage volume changes. Any external applied strain (thermal or shrinkage strain) on concrete pavements with lower elastic modulus results in lower internal stress due to the volume change in restrained condition of pavement slabs.

Referring to Figure 2.11, a greater difference in MOE is observed over a period of 56 days between the control and the rubberised concrete at 56 days compared to the 28-day test results (John & Kardos 2011).

$$\text{Reduction of MOE[\%]} = \left(1 - \frac{MOER}{MOEC}\right) \times 100 \tag{2.2}$$

where *MOER* is the elastic modulus of the rubberised samples in GPa and

MOEC is the elastic modulus of the control samples in GPa.

It meant that the stiffness and brittleness of crumb rubber concrete over a long-term period was much less compared to plain concrete.

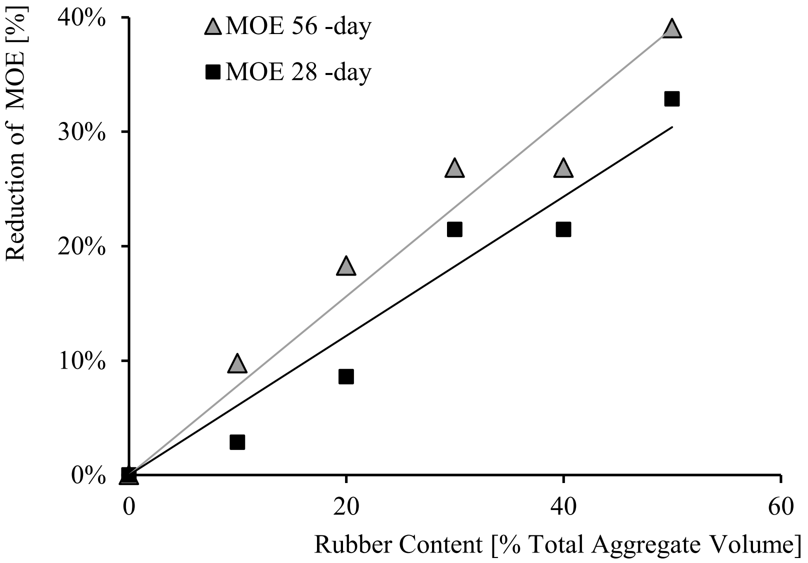


Figure 2.11: Effect of rubber content and concrete age on MOE (after John & Kardos 2011).

Studies on the effect of particle size on MOE revealed that the modulus of elasticity is less dependent on rubber particle size. In addition, the decrease pattern of the elastic modulus stays linear for rubber content up to 40% of the total aggregates (Zheng et al. 2008).

2.3 Shrinkage Properties of Rubberised Concrete

For the past several decades, the design of concrete has typically been based on the concrete strength, since it can be a simple measure for the quality control and quality assurance purposes. Although the strength requirements are frequently met, it is clear that the durability performance may not always be satisfied. Producing concrete with a required strength does not guaranty that concrete can resist against cracking (Jingfu et al. 2008). One frequently observed problem is shrinkage cracking (Qi 2003). In quasi-brittle cementitious materials such as concrete, cracking is a cause of failure (Abou-Zeid et al. 2001) and hence, any crack even minor ones can adversely impact the strength of rigid pavements (Tongaroonsri & Tangtermsirikul 2008). Although generic mechanical properties of rubberised concrete have been studied before, it is required to conduct investigations regarding other performance properties of rubberised concrete such as very early-age strength, toughness properties, plastic shrinkage properties, and the long term drying shrinkage characteristic of crumb rubber concrete.

Reviewing the literature indicates that there are limited studies available regarding shrinkage and early-age mechanical performance of rubberised concrete or mortar (Siddique & Naik 2004; Raghavan & Huynh 1998). This research aimed to enhance the know-how of shrinkage properties of CRC through systematic laboratory tests, which can illustrate the possible advantages and limitations of adding different volumes of crumb rubber into concrete.

The phenomena of shrinkage considerably impacts on the performance of restrained elements such as rigid pavements (Neville & Brooks 2010). Shrinkage can be defined as volumetric contraction of concrete over its lifetime, and can be potentially considered as a major problem for concrete pavements (Kovler & Zhutovsky 2006). Shrinkage is labelled as plastic shrinkage, when it occurs in very early age during the time that concrete is in the fresh state, while the long term shrinkage of concrete is called drying shrinkage. The magnitude of the ultimate shrinkage is a function of concrete water content and the relative humidity of the surrounding environment. For the same WC ratio, with increasing aggregate content, shrinkage is reduced. For concrete with fixed aggregate to cement ratio, as the WC ratio increases, the cement becomes more porous and shrinkage is hence also higher. Moreover, using stiffer aggregates, shrinkage is reduced (Li 2011). As can be seen in Figure 2.12, by removing aggregates from the concrete mix the amount of the generated shrinkage will increase for conventional concrete.

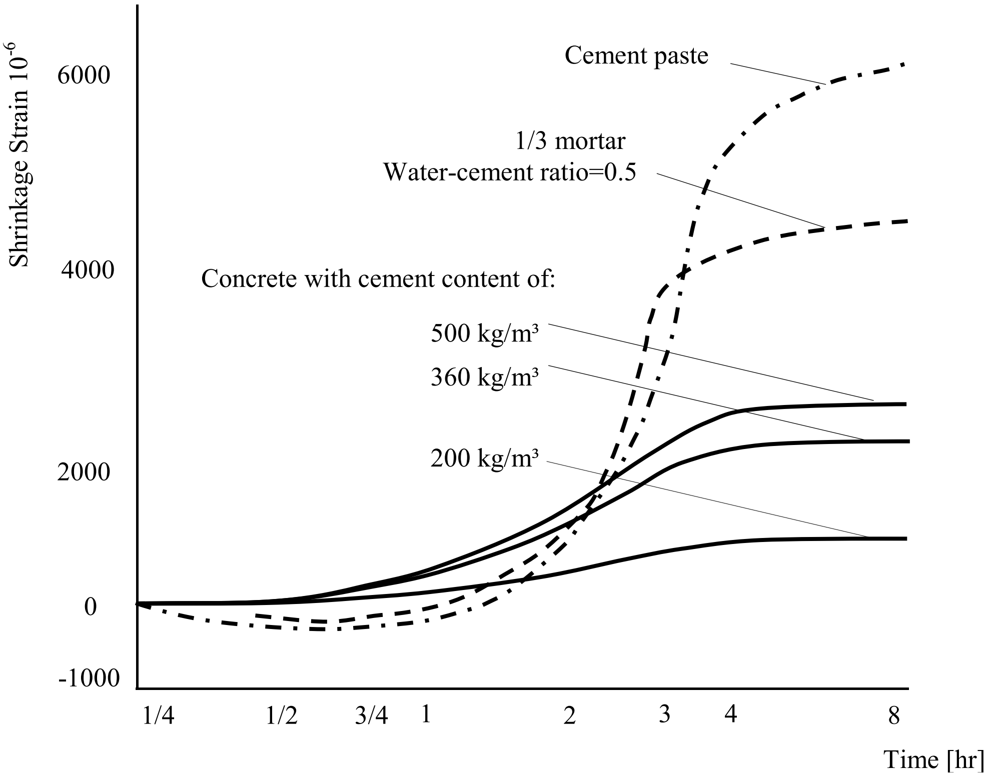


Figure 2.12: Influence of aggregate and cement contents of the mix on plastic shrinkage (after Neville & Brooks 2010)

Prevention of shrinkage cracks is often a critical parameter for concrete slabs placed on the ground (Liza et al. 2005; Sivakumar & Santhanam 2007). Although, shrinkage by itself is not a major problem for concrete pavement, it can lead to cracking of elements, which are restrained from movement. This is a particular concern in large flat structures such as highway pavements and concrete slabs with largely exposed surface areas (Weiss et al. 2000; Newman & Choo 2003).

It should be taken into account that pavement slabs are subjected to external and internal restraints. From one hand, the subbase friction provides external restraint (Boghossian & Wegner 2008). The internal restraint, on the other hand, results from aggregates, which are incompressible and resist against contraction (Radocea 1992). As a result, the internal restraint can be explained by the fact that the surface layer of concrete tries to shrink, but it is restrained by underlying layers that are not subjected to the same reduction in volume (Newman & Choo 2003). The moisture level varies throughout the concrete depth, which causes tensile stresses on the surface of concrete (Australian

DataSheet 2005). The magnitude of the ultimate shrinkage is a function of concrete water content and the relative humidity (RH) of the surrounding environment. For a same waster-cement (WC) ratio, shrinkage is reduced, by the increase of aggregates content. On the other hand, for concrete series with a fixed ratio of aggregates to cement, as the WC ratio increases, the cement paste becomes more porous and hence, the shrinkage will be boosted. Moreover, if stiffer aggregates are used, shrinkage will be reduced (Li 2011). Rubber is a low stiffness material and by replacing aggregates with rubber, the generated shrinkage increases.

The Risk of early-age uncontrolled cracking of concrete pavements must be minimised as it negatively affects the long-term performance, durability and serviceability of rigid pavements (Voigt 2002; Liza et al. 2005). The plastic shrinkage surface cracks are gates for external deteriorating agents into the concrete matrix (Boghossian & Wegner 2008; Sivakumar & Santhanam 2007). It results in corrosion of reinforcement in reinforced pavement slabs or ravelling of plain concrete pavement slabs. The durability problems are always associated with the penetration of water with or without corrosive agents into concrete. If water penetrates into concrete pavements, it results in both physical and chemical damage. The Physical damaging action of such water will then lead to spalling of concrete pavements.

Pavement shrinkage can be classified into different types. Autogenous shrinkage, carbonation shrinkage, plastic and drying shrinkage are the most important aspects of volume change, which can happen throughout the service life of concrete (Qi 2003; Neville & Brooks 2010). In Australia, the water cement ratio and the cement content of pavement mixes are usually set higher than 0.40 and less than 400 kg/m^3, respectively. Thus, only the plastic and drying shrinkage can be noted as the main types of shrinkage that concrete pavements undergo.

2.3.1 *Plastic Shrinkage Mechanisms*

It is well-established by previous investigations that concrete pavements in the plastic state are prone to the plastic shrinkage. During the first hours after concrete is casted, if the rate of water evaporation exceeds concrete bleed water, the plastic shrinkage will occur (Newman & Choo 2003), and this will result in plastic shrinkage cracks. Consequently, plastic shrinkage cracks lead to a reduction in the durability of the concrete elements (Subramaniam et al. 2005; Boghossian & Wegner 2008). Concrete is sensitive to plastic shrinkage cracks from the placement to the setting time (Powers 1969). In accordance to the previous studies, the three dimensional volume contraction of fresh concrete is defined as plastic shrinkage. This contraction generated as a result of rapid water loss from the fresh concrete (Sivakumar & Santhanam 2007), which involves a mass transfer from the surface of concrete to the surrounding environment (Mehta et al. 2006). It is believed that the loss of water can mainly happen as a result of evaporation from the highly exposed surface of pavement concrete slabs, or by absorption of pavement subgrade. The immediate plastic cracking can be revealed on the surface of concrete within a few hours as shown in Figure 2.13.

Figure 2.13: Plastic shrinkage cracking, a typical defect of pavement slabs (PCA 2001)

Moreover, the early-age shrinkage effects can leave a “weakness” on the concrete surface, where the cracks occurred on the concrete surface can develop further if any drying condition happens in the future (Australian DataSheet 2005; Subramaniam et al. 2005).

Different mechanisms have been explained to elaborate the contraction resulted from removing of water from fresh concrete. Time is a major factor playing an important role in the shrinkage of concrete. As a result, study of shrinkage at early age is significantly important (Holt & Leivo 2004; Liza et al. 2005). It can be noted that the rate of shrinkage decreases rapidly with the elapsed time. It is observed that up to 30% of the 20 year shrinkage occurs in the first two weeks after casting concrete (Siddique & Naik 2004; Neville & Brooks 2010). According to the literature, the shrinkage of concrete pavements is due to a change in the concrete moisture content, which relies on two major mechanisms. The first one is the result of surface capillary tension, and the other one, resulted from the removing of interlayer water (Kovler & Zhutovsky 2006).

Capillary Pressure Mechanism

Wittmann (1976) introduced the capillary pressure mechanism, which is defined as the contraction due to the capillary pressure of concrete mix water. The force in this case should be proportional to the surface tension of water and is inversely proportional to the radius of menisci curvature of water in capillary pores. In order to understand the nature of this contraction properly, the source of the water reaching the surface of concrete pavements and the procedure that concrete water is lost, are required to be studied.

There are three conditions, which can be considered for any concrete at fresh states. Firstly, just after casting concrete the surface of the paste is covered with a thin plane layer of water, thus, no change in the pore pressure of fresh concrete occurs in this stage. Then, fresh concrete is subjected to sedimentation and settling of the denser cement and aggregate particles due to gravitational forces. This procedure results in the rise of mix water to the top surface of the concrete pavement, which is known as concrete bleeding (Henkensiefken et al. 2010). The thin layer of bleed water extends over the surface of the concrete pavement and gradually evaporates during the first stage of drying. Once this layer evaporates, the meniscus shape pores at the surface of the concrete will be formed (Wittmann 1976). As a result, the surface of fresh concrete loses its planeness, and consequently, the magnitude of the pore-water pressure begins to increase.

Using the Laplace equation, engineers can estimate the magnitude of this tensile stress. The condition of concrete surface layer is being changed from a saturated to a partially saturated condition, when concrete dries out (Australian DataSheet 2005). As the surface dries, menisci are formed between the solid particles, therefore, the capillary tension force starts to be generated.

$$P_c = -\frac{2\gamma}{r} \tag{2.3}$$

where P_c is the capillary pressure of water on concrete pores Pa, γ is the surface tension of water in kN/m and r is the radii of menisci in m.

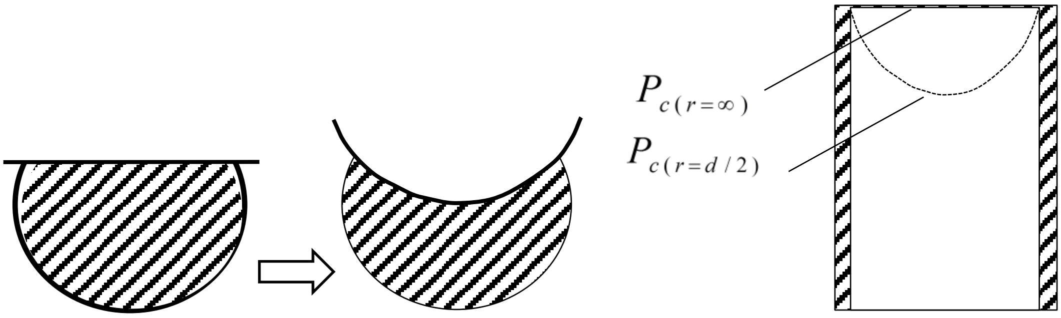


Figure 2.14: The change of capillary water pressure (adopted from Soroka 1979)

The magnitude of the shrinkage is affected by the volume of lost water from the concrete surface, which is governed by the temperature, the ambient relative humidity, and the wind velocity (Newman & Choo 2003).

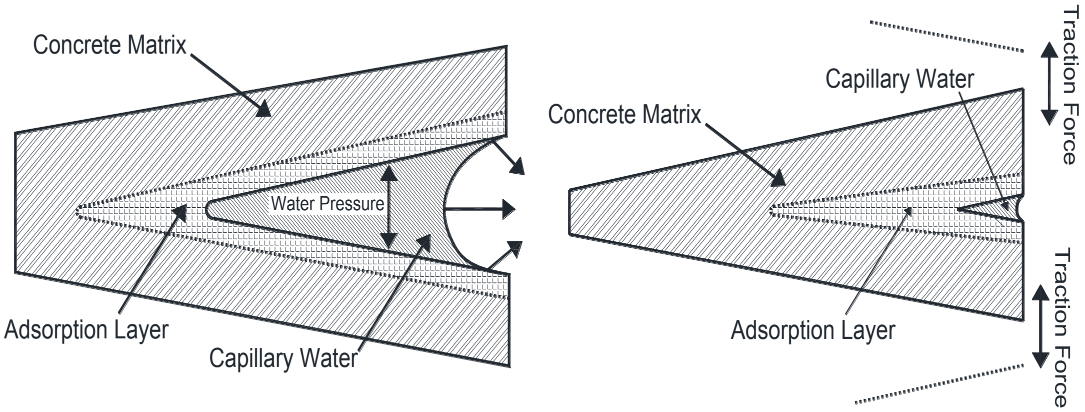


Figure 2.15: Plastic shrinkage mechanism (adopted from Newman & Choo 2003)

When the evaporation continuous, the radius of the capillary water is reduced and the capillary pressure increases. Referring to Laplace relationship, shown in Equation (2.3), water in capillaries is always under the tensile stress (Figure 2.14).

The tensile stress in capillary water must be balanced by the compressive stress of the surrounding solids (Kovler & Zhutovsky 2006). Accordingly, drying of water from capillaries will subject them to the compressive stress, bringing the neighbouring solid particles closer and results in contraction (Sivakumar & Santhanam 2007; Newman & Choo 2003) as shown in Figure 2.15.

Movement of Interlayer Water Mechanism

Cement paste is largely made of the calcium silicate hydrate (C-S-H) gel, which is oriented in laminar sheets. These sheets have large surface areas and are highly polarized with the electrical charge. The layers of C-S-H gel attract water molecules and build very thin layer water in scale of the microstructure. Removing interlayer water out of the C-S-H layers, will affect the spacing between the layers, and causes volume reduction of concrete (Figure 2.16).

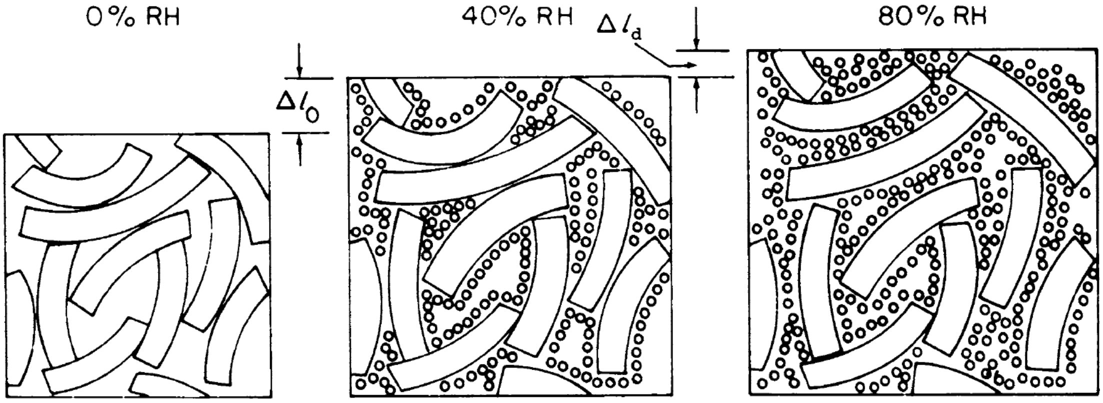


Figure 2.16: Different stages of the interlayer water vs. RH conditions (adopted from Wittmann 1982)

Shrinkage can be classified in two types of reversible and irreversible (Neville & Brooks 2010). After shrinkage occurs, if the concrete member is allowed to absorb water, only a part of the shrinkage is reversible. Although, lost water from the capillary pores can be replaced by new absorbed water, once interlayer water is removed from the interlayer space, it should be considered as an irreversible process (Li 2011)

2.3.2 Drying Shrinkage Mechanism

The loss of water from concrete in later age (>24 h) results in drying shrinkage of concrete. It is typically measured as the total free shrinkage resulting from a change of length within a specific duration of time, such as applying the test method described in the Australian Standard AS1012.13. The concrete samples are kept in the provided drying conditions, the gel water is lost continuously over the time and the concrete samples shrink. It is well established that cement paste shrinks more than mortar and in the same way, mortar shrinks more than concrete. Rubber has a lower stiffness. Therefore, substituting a portion of aggregates with rubber may result in higher drying shrinkage. As a result, the drying shrinkage of rubberised concrete is investigated in this research.

2.3.3 Measurement of Shrinkage

The potential early and long term shrinkage cracking is highly influenced by the magnitude and the rate that shrinkage develops. Moreover, the shrinkage strain is significantly affected by the element restraint and geometry (Weiss et al. 2000). Moreover, environmental conditions, such as temperature, relative humidity, and the ambient wind velocity control the magnitude of shrinkage (Sivakumar & Santhanam 2007; Holt & Leivo 2004). In order to have a clear understanding of shrinkage performance of rubberised concrete, measuring plastic and drying shrinkage should be conducted in a standard ambient condition, which is addressed in shrinkage test specifications.

Measuring Plastic Shrinkage

The recent research by Cement Concrete & Aggregates Australia (CCAA) has stated that early-age shrinkage can develop strains in concrete of similar magnitude to those resulting from the drying shrinkage (Australian DataSheet 2005). In order to evaluate plastic shrinkage properties of concrete two approaches are used. The first one is conducted by measuring of the free plastic shrinkage directly, and the second approach measures the cracking resulted from the restrained elements.

a) Evaluation of Plastic Shrinkage Based on Strain

Measuring the magnitude of the plastic shrinkage is not a simple task, compared to the drying shrinkage. Concrete in the plastic stage is semifluid. Therefore, pins such as those ones used for measuring drying shrinkage cannot be set on samples. In addition, the magnitude of plastic shrinkage varies throughout the sample depth.

Some attempts have been made for conducting such a measurement. Al-Amoudi et al. (2007) used some embedded reference gauges, which were set inside the concrete samples. The gauges were connected to linear variable differential transducers (LVDT) for measuring the plastic shrinkage strain. In another investigation, a low-modulus vibrating wire was embedment inside the slabs and used for measuring plastic strain. The frequency of the installed vibrating wire observed to be changed by the magnitude of shrinkage that concrete undergoes. Using a manufacturer-supplied calibration enabled conversion of wire vibration frequency to concrete strain (Liza et al. 2005). LVDTs were also employed by Mora-Ruacho et al. (2009) for measuring the vertical settlement of concrete samples. The vertical settlement of the mix over its height can be applied as a measure of volume reduction in fresh concrete. However, these types of tests are not accurate as the samples are subjected to external and internal restraints, which are come from the casting mould friction and concrete interlayer restrain.

b) Evaluation of Plastic Shrinkage Based on Cracking Measurement

In order to have a realistic simulation of cracking resulted from restrained plastic shrinkage different types of tests have been conducted by researchers. These tests involve performing tests on restrained slabs with stress raisers at the middle (Kraai 1985; Weiss et al. 2001), restrained ring tests (Wang et al. 2001; Kang & Jiang 2008), modified beam test (Mora et al. 2000), and slabs placed on subbase layer (Banthia et al. 1996). The average width of cracks is calculated for the cracked surface of samples manually. However, accurate measurement of plastic cracks will be a complex task and need a high level of interpretation if it is performed manually.

On the other hand, applying the “Image Analysis” of the cracked areas is reported to be a more suitable and accurate option rather than measuring crack properties manually (Chermant 2001; Mindess & Diamond 1980; Diamond & Bonen 1995). In this research, an advanced code for analysing cracks has been designed, and the results of plastic shrinkage test have carefully been analysed. The procedure of crack analysis and the outcomes are discussed in Section 3.3.6.

Although early age shrinkage of concrete is significantly important, the shrinkage model introduced in the Australian Standard AS3600 - Concrete Structures (AS3600 2009), does not distinguish the early-age shrinkage of concrete. Moreover, early-age shrinkage effects have not been measured specifically in the Australian Standard AS1012.13 for shrinkage test (Australian DataSheet 2005).

Measuring of Drying Shrinkage

Any amount of concrete shrinkage should be of concern since the higher shrinkage means the greater risks of cracking and deterioration of concrete (Holt & Leivo 2004). Shrinkage takes place over a long period, but the effect of early-age shrinkage is highly important in the total magnitude of shrinkage.

In Australia, the measurement of shrinkage is performed based on drying shrinkage test AS 1012.13 - Determination of the drying shrinkage of concrete for samples shrinkage of concrete for samples prepared in the field or in the laboratory. This test only considers the free long-term shrinkage of sample elements. In order to control cracking of concrete elements, tighter limits are being placed for the results of drying shrinkage test (Australian DataSheet 2005). However, such limits have very little impact on early-age shrinkage and the related cracking, which may occur within a day or so after the concrete sample being casted (Australian DataSheet 2005). The later development of these early-age cracks is often incorrectly diagnosed as a result of drying shrinkage at the higher age. Prevention of shrinkage cracks is often a critical parameter in the design and construction of concrete slabs (Liza et al. 2005). In Australia, this task is performed for concrete pavements by measuring the 21-day free drying shrinkage strain. In accordance with the Australian Standard AS1012.13, the measured 21-day drying shrinkage strain should be less than 450 microstrain (RTA R83 2010).

2.3.4 Shrinkage Cracking of Rubberised Concrete

Literature indicates when the concrete elements are well designed, cast and cured there should not be any noticeable cracking, and hence most shrinkage cracks can be eliminated. However, the surfaces of concrete pavements are highly exposed to the ambient conditions, which need more attention compared to other types of concrete. The previous investigations have revealed that shrinkage cracks on large exposed surfaces of concrete pavements may happen upon a combination of various factors, such as concrete early-age tensile strength, deformation capacity, and the ability of concrete to resist against fracture. The aims of the previous studies were to increase the ductility capacity of concrete to improve the concrete cracking resistance. Rubber particles have low elastic modulus in the range of 0.01 to 0.1 GPa, and are highly flexible, which can undergo large deformation. Introducing rubber into concrete has two opposite effects. The negative impact is the reduction of tensile strength, whereas the positive effect is associated with the enhancement of concrete ductility. The degree of positive and negative effects depends on the properties and content of the introduced rubber.

Different approaches can be found in the literature, regarding the reason for shrinkage cracking occurring. These approaches can be classified in three main categories, which are based on the concrete tensile strength, the concrete ultimate tensile strain capacity and, the concrete fracture capacity.

The first approach discusses the low tensile strength of concrete, especially during the concrete, plastic state. Shrinkage cracks develop on the surface of concrete, after its surface becomes set and hardened. At the same time, concrete is not strong enough yet to resist against the tensile stress resulting from the restrained shrinkage. In other words, cracking happens, when the tensile stress σ_{tsh} induced by the restrained shrinkage strain ε_{sh} exceeds the tensile strength f_t of concrete, especially at early-ages even the first hours after the casting (Collepardi et al. 2005; Boghossian & Wegner 2008; Newman & Choo 2003; Sivakumar & Santhanam 2007).

$$\sigma_{tsh} \times A = (E \times \varepsilon_{sh}) \times A \geq f_t \tag{2.4}$$

where σ_{tsh} is the tensile stress resulted from shrinkage in MPa, ε_{sh} is the shrinkage strain in microstrain, E is the concrete elastic modulus in GPa, f_t is concrete tensile strength in kN and A is the cross sectional area of the element subjected to the tensile stress in mm^2

As can be seen from Equation (2.4), shrinkage cracking is not only a function of concrete constituent properties, but also highly dependent on the concrete element size and geometry (Weiss et al. 2000). Two concrete elements with the same constituents and ambient conditions, but with different geometries, may substantially undergo different shrinkage cracking.

The second approach includes the shrinkage cracking definition, based on the ultimate strain or the elongation capacity, which is considered as an important parameter, indicating the crack-resistance behaviour of concrete (Khorrami et al. 2010). In this approach, shrinkage cracks may happen at any time, when the generated shrinkage tensile strain exceeds the ultimate tensile strain capacity of concrete structures (Holt & Leivo 2004). As can be seen in Figure 2.17 samples with the same tensile strength of 5 MPa have different strain capacities (Tongaroonsri & Tangtermsirikul 2008).

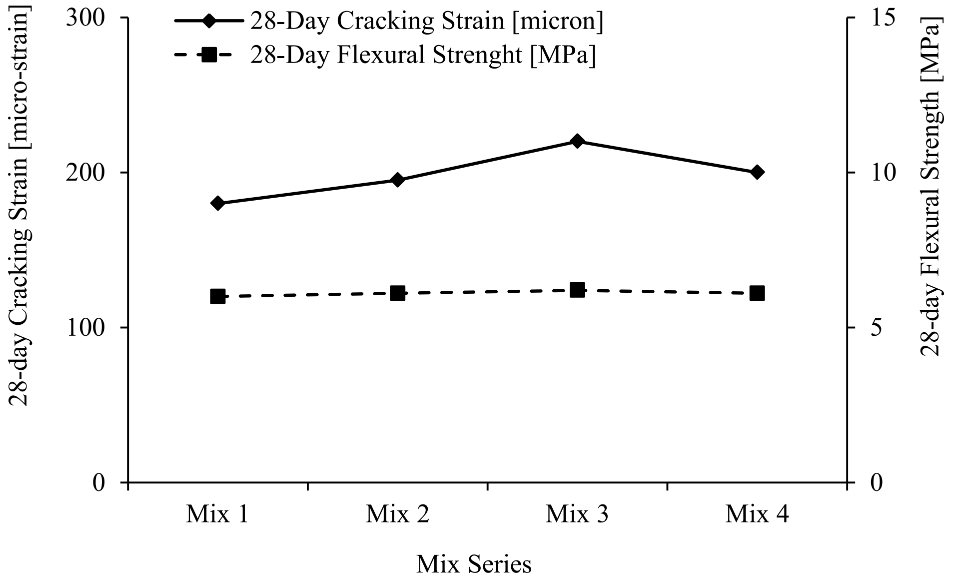


Figure 2.17: Mix series with equal flexural strength and different ultimate strain (Tongaroonsri & Tangtermsirikul 2008)

Therefore, two concrete samples with a same tensile strength can perform substantially different regarding shrinkage, due to different ultimate tensile strain capacities. Early age plastic shrinkage is a concern because, during the early hours after casting, strain capacity of concrete pavement has its minimum value (Emborg 1989; Byfors 1980). Concrete is vulnerable to external or internal applied stresses as demonstrated in Figure 2.18. Investigation performed by Byfors (1980) revealed that concrete has the lowest tensile strain capacity in the early hours after it is set but has not gained enough tensile strain capacity.

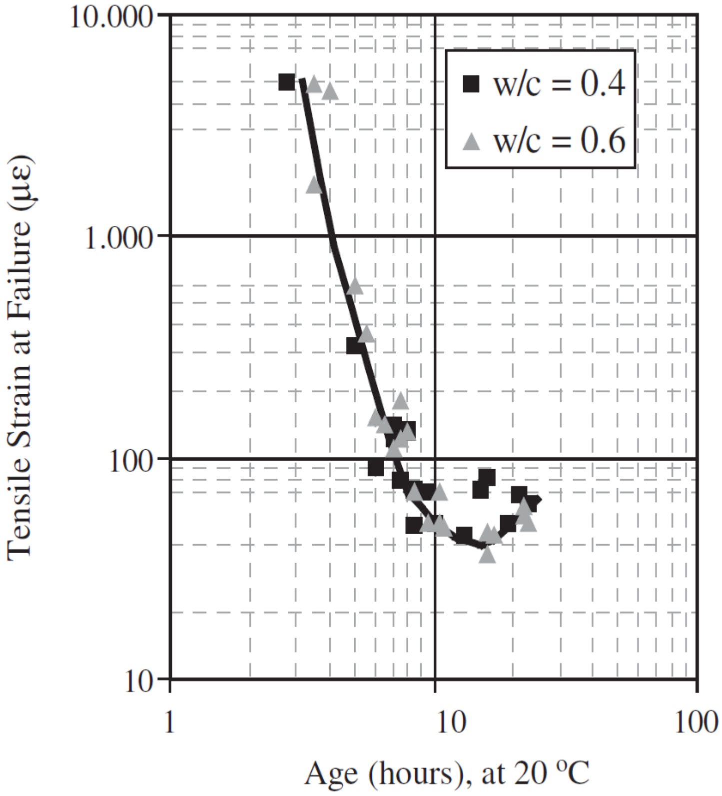


Figure 2.18: Decrease of tensile capacity during early ages (Byfors 1980; Emborg 1989)

Finally, the third approach is the fracture based approach, which attempts to provide an explanation for shrinkage cracking characteristics by investigating fracture-based failure of concrete (Kang & Jiang 2008; Weiss et al. 2000; Subramaniam et al. 2005). This approach might be better aligned for studying of shrinkage cracking especially in brittle materials, because the combination of sensitivity to crack propagation and high tensile stress at the stage of failure is considered in this approach. On the basis of concrete fracture property, it can be indicated that when the shrinkage energy exceeds the fracture energy of concrete, cracking occurs on the surface of concrete (Kang & Jiang 2008; Subramaniam et al. 2005).

There is no standard test available for measuring toughness of rubberised concrete. If the toughness test is conducted based on energy measuring methods, an optimum content of rubber may be determined by maximising the area under the load-deflection curve. It was reported that an increase in toughness was achieved by adding rubber to concrete (Topcu 1995). In another study the load-displacement curve of tensile tests were plotted for both plain concrete and concrete containing 20% of rubber by volume of fine aggregates. Experimental results revealed that the normal concrete had a faster failure compared to the rubberised concrete (Balaha et al. 2007). However, a slow failure does not mean a high toughness of concrete. The reviewed test results available from the literature imply that compared to plain concrete, rubberised concrete had higher energy absorption capability during failure (Segre & Joekes 2000; Topcu 1995), also had limited residual capacity after the failure (Eldin & Senouci 1994).

The low-stiffness rubber particles play three roles to limit the shrinkage cracks by reducing the internal restraint, lowering of the elastic modulus and trapping cracks from propagation in concrete. Concrete aggregates are solid particles resisting against the shrinkage. The restraint offered by aggregates results in shrinkage cracking of concrete (Radocea 1992). Replacing a portion of aggregates with a highly elastic rubber reduces the internal restraint of concrete and lowers the concrete elastic modulus. It can be seen from Equation (2.4) that lower elastic modulus may lead to lower thermal and shrinkage stress. In addition, Crumb rubber particles in the concrete matrix, trap cracks and do not let them pass through. Hence, it can be considered as a momentum reducing effect of rubber particles on crack propagation (Khorrami et al. 2010), which may provide resistance against shrinkage cracking. The shrinkage crack property of rubberised concrete is investigated in this research.

In a study conducted by Raghavan et al. (1998), rubberised mortar properties containing different portions of rubber particles in average length of 5mm to 10 mm were assessed by evaluating the resistance of rubberised mortar against the plastic shrinkage cracking. It was observed that all specimens were cracked within the first three hours of placement. Moreover, it was indicated that modifying mortar with rubber had the key effect on allowing multiple cracks to occur over the width of the specimen, when it was compared with an intense single crack on the top surface of mortar prepared without rubber. Moreover, the total crack area in the case of rubber-filled mortar, found to be decreased with an increase in the rubber content (Raghavan et al. 1998).

It is noted that the crack resistance of the mortar contained crumb rubber with the size of 1.5 mm was improved substantially by adding crumb rubber particles (Kang & Jiang 2008). Kang & Jiang (2008) reported that adding rubber led to a reduction in both the tensile strength and the generated shrinkage stress, but the degree of reduction was found to be different for various content of rubber. It was found that when rubber fraction was less than 20% in volume, the cracking time was retarded and shrinkage properties were improved.

Another study investigated the development of the free drying shrinkage of rubberised concrete over 150 days (Jingfu et al. 2008). That study indicated that by increasing the rubber content the drying shrinkage increased. However, the higher free drying shrinkage will not result in higher shrinkage cracking if the strain capacity of concrete is enhanced. The free drying shrinkage test cannot provide clear understanding of shrinkage cracking behaviour of rubberised concrete without the study of restrained plastic shrinkage and fracture behaviour of concrete.

In a recently conducted research by Bravo & de Brito (2012) drying shrinkage of different rubberised concrete mixes with different water-cement ratios between 0.43 and 0.48, were investigated. Different sizes of recycled rubber, prepared by different processes were examined. The results of that study showed that there is a significant positive correlation between rubber content and drying shrinkage. In addition, it was observed that increasing the content of fine size crumb rubber resulted in higher drying shrinkage (Bravo & de Brito 2012). Similar results were reported Sukontasukkul & Tiamlom (2012) for drying shrinkage of rubberised concrete samples and by Uygunoğlu & Topçu (2010) regarding rubberised mortar drying shrinkage.

2.4 Summary and Identifying Research Gaps

The term of rubberised concrete is a general term, which involves all types and sizes of recycled rubber. Although much research has been conducted thus far on the concept of using recycled rubber in cementitious composites, very limited studies have been performed on the application of crumb rubber concrete (CRC) for rigid pavements. The aim of this research is to extend the knowledge of crumb rubber concrete characteristics used for the pavement application.

Studying the challenges associated with the production of concrete mix with crumb rubber and introduction of methods to mitigate the relevant challenges are significantly important. Those challenges involves difficulties in the determination of proper content of rubber in the mix, determining the specific gravity of crumb rubber accurately, the best method of adding rubber into the mix, and problems regarding vibration and compaction of crumb rubber concrete.

It is required to establish an experimental relationship for predicting the strength properties of CRC by considering the effects of different variables, such as the concrete age, the rubber content and the water-cement ratio.

Moreover, it is necessary to conduct an in-depth investigation regarding the advantages of treating rubber before adding into the concrete mix. It includes trialling an innovative treatment method termed water-soaking of rubber and also optimising the sodium hydroxide (NaOH) treatment of crumb rubber on rubberised concrete properties.

There are not any proper guidelines for employing CRC for rigid pavements based on the local Australian specifications. This study introduces detailed research following the Austroad standard and the New South Wales Authorities guidelines in preparation of concrete for pavement applications. Moreover, local typical cement, sand and coarse aggregates, and the local recycled waste tyre particles are used for all test series.

Another important stage of this research is associated with investigation on the possibility of adding recycled rubber into the concrete mix in order to improve the shrinkage properties and crack-resistance of concrete. Only a limited number of studies are available, concerning the plastic shrinkage and cracking of concrete containing rubber particles.

Chapter 3

Experimental Program

3.1 Research Materials

3.2 Identification of Mix Arrays

3.3 Research Specifications and Test Methods

3.1 Research Materials

This chapter is dedicated to describing the experimental program. It involves the introduction of different constituents of rubberised concrete and other materials utilised for this research, as well as the testing methods used for evaluating different properties of rubberised concrete. Moreover, the Australian pavement design criteria, used for assessment of the test results are introduced. Several concrete mixes have been prepared using materials with specific properties contents explained as follows.

3.1.1 Shrinkage Limited Cement

The Shrinkage Limited (SL) type cement has been used in this study. This cement type is designed for applications, where there is a desire to minimise concrete drying shrinkage such as pavement construction. Characteristics of cement utilised in this study, represented in Table 3.1, which satisfied specification requirements of AS3972 - General purpose and blended cements (AS3972 2010) .

Table 3.1: Properties of the used shrinkage limited cement vs. AS3972 requirements

Property	AS3972 limits	Properties of project cement
Initial setting time	>45 minutes	60 – 150 min
Final setting time	<10 hours	150 – 210 min
Soundness	<5 mm	<3 mm
28day Standard mortar drying shrinkage	<750 µstrain	550 µstrain
7day standard mortar compressive strength	>35.0 MPa	43 – 52 MPa
28day standard mortar compressive strength	>45.0 MPa	54 – 62 MPa

A recent study carried out by Yurdakul (2010), aimed to find the optimum cement content in concrete pavements. The optimum cement content was trialled for different WC ratios in order to achieve proper requirements regarding mix workability, strength, and durability. Moreover, the investigated optimum content was determined, considering the reduction of the carbon dioxide emission, energy consumption and costs. An experimental program was conducted by Yurdakul (2010) involved testing 16 concrete mix series with various WC ratios (0.35, 0.40, 0.45 and 0.50) and with different contents of cement (i.e. 240, 300, 355 and 415 kg/m^3). The study concluded that 300 to 355 kg/m^3 was the optimum cement content for conventional concrete.

In addition, previous research adding rubber into concrete mix was reviewed for determining a proper and conventional range for the cement content. John & Kardos (2011) stated that the cement content in range of 300-400 kg/m^3 utilised for preparing rubberised concrete. Zheng et al. (2008) mentioned the use of 400 kg/m^3 cement, while Taha et al. (2009) reported selection of cement content 350 kg/m^3. Lastly, Altoubat et al. (2001) investigated mixes with cement content of 362 kg/m^3. Taking into account all the performed studies in the past 370 kg/m^3 cement content is selected for preparation of research mixes. This content was marginally higher than the recommended content suggested for conventional concrete by Yurdakul (2010). Considering the reported cement content in previous studies and the negative impact that introduction of rubber has on the concrete strength, cement content was selected marginally higher than the optimised content range suggested by Yurdakul (2010) for conventional concrete.

It was reported that a limited addition of fly ash is allowed in pavement concrete mix. Adding fly ash is conducted for compensating aggregate grading deficiencies, reducing concrete shrinkage and improving workability and durability of concrete. Moreover, it offsets the usage of cement and hence reduces the costs, because cement is the most expensive component in pavement concrete. The applied fly ash quantities vary from nil to about 70 kg/m^3. However, the minimum total cementitious binder content (fly ash plus cement) should always be kept higher than 300–330 kg/m^3 range, which Austroad Standard suggested (Austroad 2009). It is addressed by specification that the minimum cementitious content of 300–330 kg/m^3 is typically specified for durability reasons.

The use of about 20% fly ash has become a routine practice in Australia. However, no fly ash was used in this study. It was decided to remove one extra variable from the investigation and to lower the complexity of the analysis. This decision was set based on the effects that both rubber and fly ash have on strength gaining of concrete.

It was reported by Khatib & Bayomy (1999) that the addition of more rubber resulted in less compressive strength gain of concrete samples from 7 to 28 days (Figure 3.1). It was revealed that by introduction of 30% or more rubber into the concrete mix, the 28-day compressive strength remained in the same magnitude of the 7-day compressive strength.

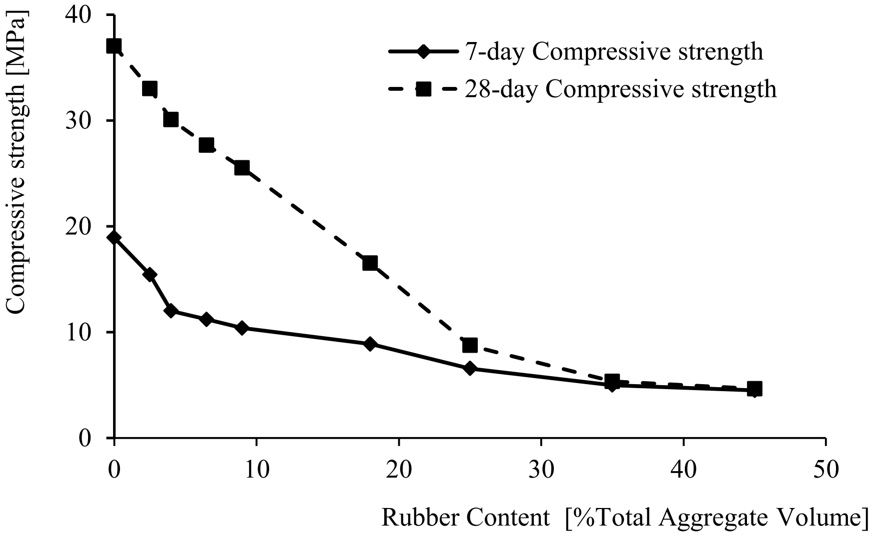


Figure 3.1: The effect of crumb rubber addition on strength gaining pattern (Khatib & Bayomy 1999)

Strength gaining is primarily a function of the hydration rate of cement and fly ash in a given mix (Pierce & Blackwell 2003). Previous investigations revealed the negative effects of adding rubber in the mix on the strength of concrete (Khatib & Bayomy 1999; Khorrami et al. 2010). Utilising both of the fly ash and crumb rubber in the pavement mix possibly results in complexity of strength gaining analysis for the prepared concrete. Moreover, it was reported by Youssf & Elgawady (2013) a better adhesion between rubber surface and pozzolanic constituents formed, which may result in improvement of rubberised concrete strength. In order to avoid any unwanted gain in strength of rubberised concrete due to the use of fly ash, it was decided to prepare mix series without fly ash. This enabled performing study of the pure negative impacts of introducing rubber on mechanical and shrinkage properties of rubberised concrete.

It is aimed that the trend of strength gaining for rubberised concrete becomes clear by this research. Moreover, the improving effects of different methods of rubber treating are investigated. Accordingly, considering the provided information by this study, for any future research, mixing fly ash with the cement is strongly suggested. The result of utilising fly ash in cementitious material can be compared with the current results to make a wider framework of understanding of introducing rubber into concrete mix.

3.1.2 Fine and Coarse Aggregates

Austroads specification provided two boundaries for the combined aggregates used in the typical pavement concrete grading (Austroad 2009). In addition, NSW RTA specifications provided the same limits for the combined aggregate particle size distribution (RTA R83 2010), which are demonstrated in Table 3.2.

Table 3.2: Pavement aggregate sieve analysis vs. Australian Standards requirements

Sieve size	Crumb Rubber	Fine aggregates 0.075 to 4.75mm		Coarse aggregates 10mm (nominal size)		Coarse aggregates 20mm (nominal size)		Combined aggregates	
[mm]	Passing [%]	Limits[1] [%]	Passing [%]	Limits[1] [%]	Passing [%]	Limits[1] [%]	Passing [%]	Limits[2] [%]	Passing [%]
26.50	-	-	-	-	-	100	100	100	100
19.00	-	-	-	-	-	85 to 100	95	95 to 100	98
13.20	-	-	-	100	100	-	51	75 to 90	80
09.50	-	100	100	85 to 100	87	0 to 20	14	55 to 75	62
04.75	100	90 to 100	98	0 to 20	11	0 to 5	4	38 to 48	40
02.36	60	60 to 100	81	0 to 5	3	-	3	30 to 42	32
01.18	35	30 to 100	65	0 to 2	2	0 to 2	2	22 to 34	25
0.600	5	15 to 80	55	-	-	-	-	16 to 27	20
0.300	0	5 to 40	36	-	-	-	-	5 to 12	12
0.150	-	0 to 25	8	-	-	-	-	0 to 3	3
0.075	-	0 to 20	4	-	-	-	-	0 to 2	1
Absorption[%]	0.89	1.2		1.8		1.6			
Density[kg/m^3]	1150	2650		2700		2710			

[1] Australian Standard AS 2758.1

[2] Austrods Standard (Austroad 2009) and RTA specification (RTA R83 2010)

The fine and coarse aggregates used to accomplish this investigation were sourced from Dunmore, Australia. It involved 10 mm and 20 mm crushed Latite gravels were employed as coarse aggregates. The available resource of sand was 50/50 blended fine/coarse sand. All types of aggregates shown in Table 3.2 complied with the concrete grading requirements of the Standard AS 2758.1. The particle size distribution of fine and coarse aggregate sieving test method followed in accordance with the Standard AS1141.11.1 standard. Moreover, particle size distribution of rubber was investigated according to the test Standard ASTM D5644.

All fine and coarse aggregates were prepared to surface saturated dry (SSD) condition prior to batching. Therefore, the water absorption percentage and saturated surface dry density of aggregate were determined in accordance with AS1141.5 test. The achieved results are presented in Table 3.2.

Finally, the mix design of main mixing arrays sets used for this study followed the typical mix design introduced by Austroad Guidelines (Austroad 2009) as it is demonstrated in Table 3.3.

Table 3.3: Typical Pavement constituent percentage introduced by Austroad

Constituent	Austroad	WC = 0.40		WC = 0.45		WC = 0.50	
	By mass [%]	Constituent [kg/m³]	By mass [%]	Constituent [kg/m³]	By mass [%]	Constituent [kg/m³]	By mass [%]
Coarse aggregates	≈47%	1103	47%	1073	46%	1040	45%
Fine	≈32%	735	31%	715	31%	700	31%
Cementitious	≈15%	370	16%	370	16%	370	16%
Water	≈6%	148	6%	167	7%	185	8%

As can be seen in Table 3.3, all the main mix series prepared for this investigation were well fitted in the constituents breakdown percentage provided by Austroad (2009).

3.1.3 Crumb Rubber

Results of Sieve analysis and moisture content for rubber particles are shown in Table 3.2. In order to find the correct proportion of crumb rubber in the concrete mix, it was necessary to determine the specific gravity (SG) of crumb rubber accurately. The specific gravity of crumb rubber is defined as the ratio of rubber weight in air to the weight of an equal volume of water at a certain temperature, which included the weight of water within the voids. According to AS 1141.5, the standard temperature for water should be set at 23±3°C.

Four series of rubber samples were tested in this investigation. A de-airing chemical admixture was acquired and used for preparing two series of samples. Following the approach presented by John & Kardos (2011), the acquired de-airing liquid was added to the water with the ratio of 1:10 (John & Kardos 2011). A large quantity of solution was made to be sufficient throughout the entire testing process. The de-airing agent was implemented in two series of mixes as an alternative option. Previous research (Sukontasukkul & Tiamlom 2012; Sgobba et al. 2010) reported formation of trapped air bubbles, when rubber was added to water. The trapped air bubbles are considered as a source of error in calculation of specific gravity. It was reported that the trapped air bubbles between rubber particles, resulted in floating of waste tyre particles. Hence, removing trapped air bubbles from the mix was attempted.

Four series of samples were prepared as illustrated in Figure 3.2. Samples (a) and (b) were prepared with pure water. On the contrary, the mix of water and defoamer applied for preparing mix series of (c) and (d). Afterwards, test procedures, followed in accordance with both Australian AS1141.5 and ASTM C-128 standards. The specific gravity test was conducted instantly after mixing rubber and liquid for two mix series, presented in Figures 3.2 (a) and (c). In contrast, the test for mix series demonstrated in Figures 3.2 (b) and (d) were conducted 24 hours after mixing of rubber and the liquid.

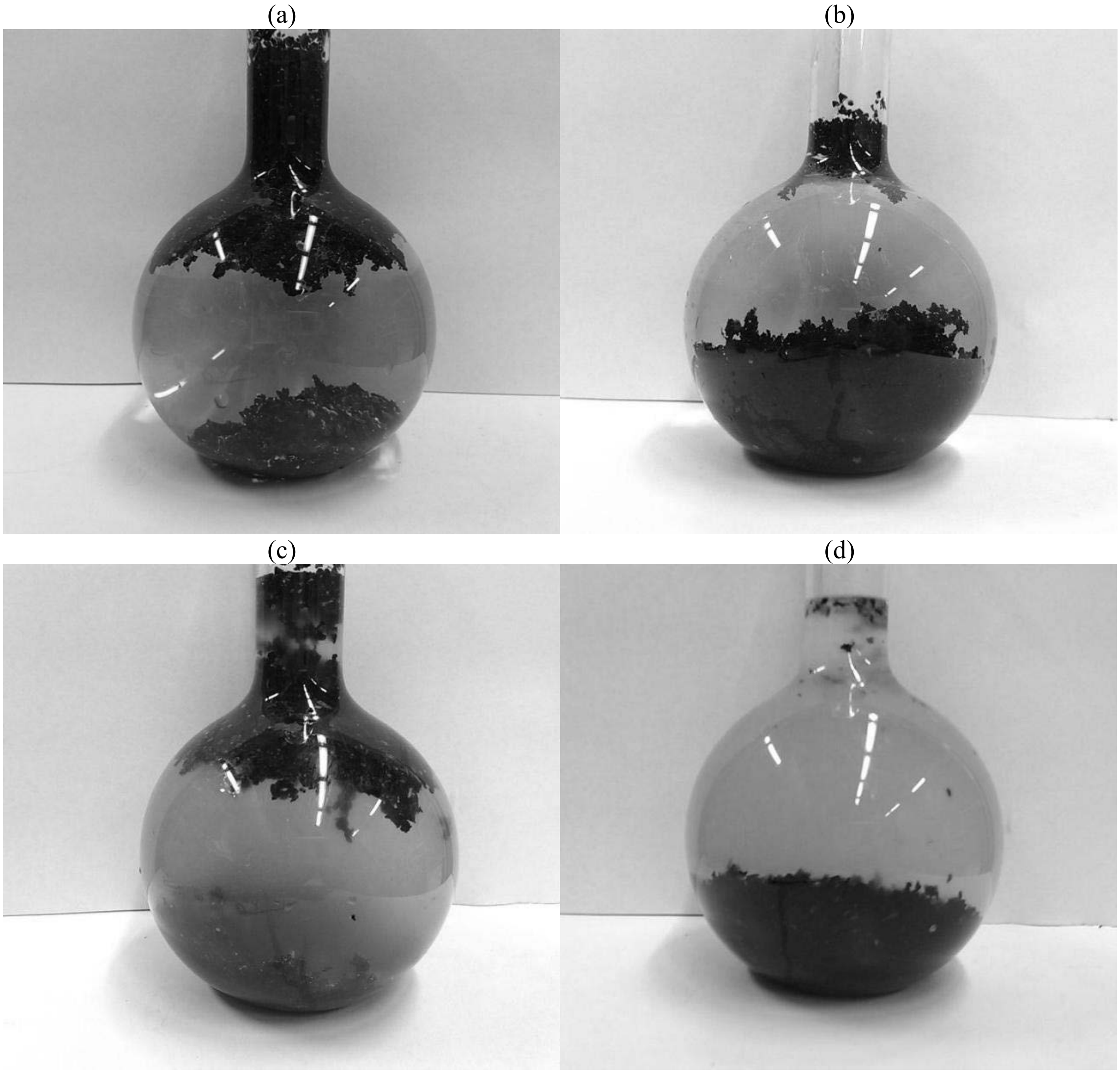


Figure 3.2: Rubber added to water (a) instantly after mixing, (b) after 24 hours; rubber added to a water plus defoamer (c) instantly after mixing, (d) after 24 hours

As can be seen in Figure 3.2, after passing 24 hours of conditioning, rubber particles tended to be submerged into the liquids. After passing of 24 hours, there was no noticeable difference between the mix series contained defoamer and that one without the defoamer, as demonstrated in Figures 3.2 (b) and (d). The final test results for SG are summarised in Table 3.4.

Table 3.4: Test series used for determining crumb rubber specific gravity

Mix ID	Condition of SG measurement	Liquid used for the test	SG AS 1141.5	ASTM C-128
Series1	Instantly measured	Water	1.05	1.04
Series2	Instantly measured	1:10 Defoamer:Water	1.07	1.06
Series3	After 24 hours soaking measured	Water	1.14	1.14
Series4	After 24 hours soaking measured	1:10 Defoamer:Water	1.16	1.15

Submerging crumb rubber for a period of 24 hours in water significantly reduced the number of the floating particles and removed a large portion of entrapped air bubbles from the mix. In this case, the solution of water and 1:10 defoamer provided a slightly better outcome. However, the effect of defoamer was not significant, and it was concluded that there is no need to use defoamer for conducting the specific gravity test for crumb rubber.

In contrast, the 24 hours of submerging approach played a very significant role in contribution of fixing the trapped air bubble and floating rubber issues. After 24 hours almost all particles were submerged in the liquid. Figure 3.2 (c) illustrated that applying the solution of water and defoamer did not mitigate the issue just after the introduction of rubber into the liquid.

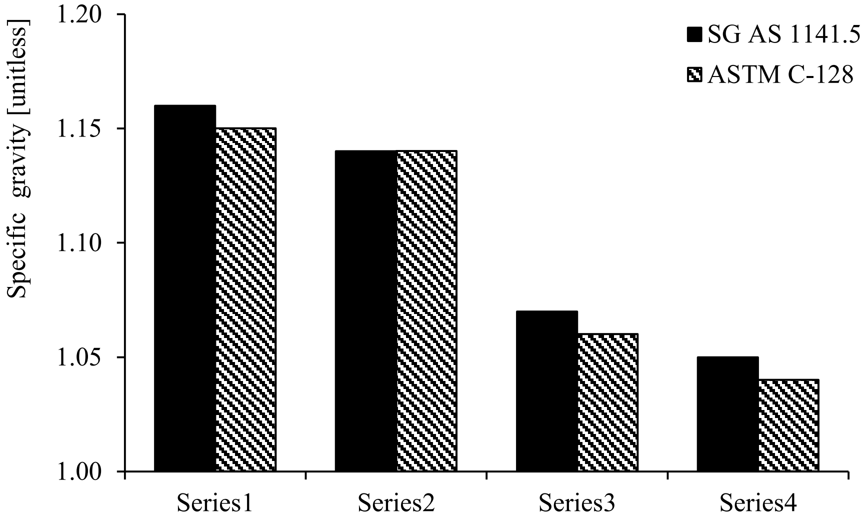


Figure 3.3: Specific gravity of crumb rubber particles determined by using different measurement methods

The test results, measured instantly after mixing rubber and liquid, were similar for both mix series prepared with water and water plus defoamer. However, after 24 hours the result of water plus defoamer was slightly better than the container with water only as presented in Table 3.4 and Figure 3.3.

According to the test results, submerging crumb rubber for a day in water reduced the trapped air bubbles highly, and also, helped avoiding the problem with the floating of the rubber particles. The trapped air and floating rubber are common problems in both specific gravity test and concrete mixing. Further information regarding submerging rubber in water for a period of 24 hours is provided under the title of "Water-Soaking Method of Adding Rubber into Mix" in Section 4.3.1.

3.1.4 Admixtures (Water Reducer, Air Entrainer and Defoamer)

Introduction of three categories of admixtures, which are commonly used for concrete pavements, were investigated in this study. It involved water reducers (WR), air entraining admixture (AEA) and defoamer (de-airing agents). Water-reducing admixtures are groups of products that are added to a concrete mix for achieving certain workability (slump number). Using WR, the same level of workability can be achieved at a lower water-cement (WC) ratio (Mailvaganam & Noel 2002). Moreover, WR 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. Furthermore, they improve the properties of concrete containing marginal or low quality aggregates and facilitate in placing concrete under difficult conditions (FHWA Materials Group 2011a). Water-reducing admixtures can be categorised into the three main groups according to their active ingredients as follows (FHWA Materials Group 2011b; Mailvaganam et al. 2002):

a) Hydroxylized carboxylic acids Salts
b) Lignosulfonic acids Salts (Lignins)
c) Polymeric materials

Use of water reducer admixtures usually decreases the water demand by 7-10%. In addition, a higher dosage of admixtures could result in a lower water-cement ratio (FHWA Materials Group 2011b). However, the Australian Road Authority guides set a limit for the content of WR, which can be added to pavement concrete (Approved Supplier List 2013). It is reported that excessive addition of WR into the mix had negative impact on the plastic property and the cohesiveness of concrete mix and should be avoided.

Literature denoted that Hydroxylized carboxylic acids admixtures are mostly used for high-slump concrete, where the slump number is over 100 mm. It was found that the lignosulfonate based admixtures could perform better for this research because they entrain less air, and consequently have less effect on mechanical properties of concrete.

Moreover, application of lignosulfonate based results in mix with better cohesiveness. Increasing cohesiveness was significantly preferable for this research, because of the difference between the constituents' unit weights of rubberised concrete. Rubber had specific weight of approximately 1 kg/m³, while this value was 2.2 kg/m³ for cement paste. In addition, fine and coarse aggregates had unit weights of 2.6-2.7 kg/m³. As a result, combining these ingredients increases the possibility of segregating. It is well-known that using WR admixtures increases the concrete strength. It was indicated that by utilising lignosulfonate base admixtures, the flexural strength increased about 10% (Mario et al. 1984). Lastly, Lignin based admixtures have been widely used in pavement industry. Austroad reported that lignosulphonates water-reducing admixtures act to disperse the cement more readily throughout the water and eliminate "clumping" of the cement (Austroad 2009).

It was noted that rubber particles, having non-polar nature, causes a tendency to entrap air in their rough surfaces (Khaloo et al. 2008). Furthermore, when rubber was added to the concrete mix, it attracted air and showed a tendency for repelling water (Richardson et al. 2002; Youssf & Elgawady 2013; Taha et al. 2009; Siddique & Naik 2004). It was reported that this behaviour (repelling water and attracting air bubbles) resulted in the adherence of air bubbles to the rubber particles, which led to entrapping of air bubble into the rubberised concrete mix. Overall, it is indicated that an increase in crumb rubber content led to a higher air content, compared to the mix prepared without rubber (Siddique & Naik 2004). Accordingly, in order to counteract the foaming effect of rubber addition to concrete, addition of defoamer to rubberised mix was considered a valid option. As a consequence, applying the de-airing agent was trialled to reduce the air content of concrete mix by John & Kardos (2011).

According to the data presented in Table 3.5, replacement of sand with rubber by a volume up to 40% (20% of total aggregates) resulted in inclining the air content (AC) up to 10%. Therefore, it was decided to utilise the defoamer admixture, if only the result of trialling mix series, proved that those mix series suffered from significant high air content. It is well-understood from traditional concrete practices that air entrainment (up to approximately 9% air content) can increase the durability of the hardened concrete and increase the workability of the fresh concrete. Different investigations illustrated that rubber tyre particles (typically 1-12mm) entrapped air bubbles in the concrete mix (Khatib & Bayomy 1999). Accordingly, based on the achieved trialling results, it was revealed that there is no need for adding air entraining admixture (AEA) into the prepared rubberised mix series.

Table 3.5: Typical admixtures in different studied

Reference	28day f'c	Slump	Test results			Admixture Types[3]		
			Air content [%][1] (no rubber)	Air content [%]				
	[MPa]	[mm]		Air [2] Content [%]	Rubber Content[%]	DA	WR	AEA
(Rangaraju et al. 2012)	40 to 60	150	1.8%	2.5%	24%	✓	✓	✓
(John & Kardos 2011)	20 to 50	60-200	5.0%	6.0%	25%	✓	✓	✓
(Zachar et al. 2010)	3 to 20	80-215	-	20%	100%	×	✓	×
(Bewick et al. 2010)	40	75-200	2.9%	4.0%	20%	×	×	×
(Jingfu et al. 2008)	40	0	-	-	-	×	✓	×
(Kaloush et al. 2005)	3 to 32	125-25	3.0%	33%	75%	×	×	×
(Khatib & Bayomy 1999)	38	80	1.0%	4.0%	50%	×	×	×

[1] The measured air content when no rubber was used; [2] The measured air content when the ratio of rubber volume to the total concrete aggregate is R; [3] DA= deairing agent, WR= water reducer or high range water reducer, AEA= air entraining admixture

The selected admixture for this study was Sika Plastiment10, which was especially formulated based on lignosulfonates. The additional compounds incorporated to it aids in placing and finishing of concrete. Sika Plastiment10 is recommended by its manufacturer for use in all applications, where high quality concrete with superior workability and normal setting times is required. Moreover, a homogeneous concrete with improvements in plastic properties can be achieved if this water reducer is used. In addition, it enables concrete to achieve internal cohesiveness with improved placement properties. As a result, by having a better cohesion, the segregation and bleeding deficiencies can be minimised. It was expected that using Sika Plastiment10 WR improves the slump, and at the same time enhances the cohesiveness and plastic properties of concrete. The positive effects are beneficial to mitigate the negative effects of adding crumb rubber into concrete.

3.1.5 Water

The selected water for this research was potable water conditioned to the temperature of 23 ± 2°C and utilised for all mix series. In addition, the volumes of water were calculated for each array of samples based on the designed water to cement (WC) ratios. Different WC ratios and also the relevant volumes of water for each array of concrete samples are listed in Table 3.6.

Table 3.6: Different examined water-cement ratios in this research

Water-Cement (WC)	Cement Content [kg/m^3]	Water Content [kg/m^3]
0.35	370	130
0.40	370	148
0.45	370	167
0.50	370	185
0.55	370	203

3.2 Identification of Mix Arrays

As mentioned earlier this research involves the assessment of different rubberised mix series in order to find the optimum content of crumb rubber, which should be added to the mix series to achieve the most promising performance. Accordingly, different series of concrete mixes were prepared and tested. The research mix arrays can be classified based on the purpose, which they are prepared. The experimental program of this research includes three stages as explained in Section 4 under the title of "Results and Discussion." The main classes of mix series are summarised as follows:

a) Trial mix series and mix proportioning

b) Selection of the treatment method for crumb rubber

c) Mechanical and performance studies of rubberised mix series

Firstly, fourteen sets of trial mixes were prepared for investigating the applicability of the selected ranges for water cement ratios and crumb rubber (CR) content (Table 3.7).

The mix identification for each design provides details regarding the four mix components, which are briefly expressed here with, [mix type] [WC ratio] [rubber content] [method of treating rubber]. For instance, T/0.35/20CR means a "Trial" mix with WC ratio of 0.35 and crumb rubber content of 20% by volume of fine aggregate, which prepared by water soaking method. The method of treating is considered to be "water soaking" method for all mix series by default, unless it is expressed to be another method.

Table 3.7: Properties of different trial mix series

Mix ID	WC	Cement	Sand		Coarse aggregate		Water	Rubber		Total
			Volume	Weight	10mm	20mm		Volume	Weight	
		[kg/m^3]	[%]	[kg/m^3]	[kg/m^3]	[kg/m^3]	[kg/m^3]	[%]	[kg/m^3]	[kg/m^3]
T/0.35/00CR[1]	0.35	370	100	695	427	766	130	0	00	2387
T/0.35/20CR	0.35	370	80	556	427	766	130	20	61	2309
T/0.35/40CR	0.35	370	60	417	427	766	130	40	122	2231
T/0.40/00CR	0.40	370	100	677	416	746	148	0	00	2356
T/0.40/00CR	0.40	370	50	339	416	746	148	50	148	2166
T/0.40/00CR	0.40	370	30	203	416	746	148	70	207	2090
T/0.45/00CR	0.45	370	100	658	404	726	166	0	00	2325
T/0.45/20CR	0.45	370	80	527	404	726	166	20	58	2251
T/0.45/40CR	0.45	370	60	395	404	726	166	40	115	2177
T/0.45/50CR	0.45	370	50	329	416	746	148	50	145	2154
T/0.45/60CR	0.45	370	40	263	416	746	148	60	174	2117
T/0.45/70CR	0.45	370	30	197	416	746	148	70	203	2080
T/0.50/20CR	0.50	370	80	512	393	706	185	20	56	2222
T/0.55/20CR	0.55	370	80	497	382	685	203	20	54	2193

[1] [mix type] [WC ratio] [rubber content] [method of treating rubber] T/0.35/00CR refers to "Trial" mix with WC of "0.35" and 0% of rubber prepared with water soaking method.

The trial proportioned mix results led to concrete mix design proportions that were further refined for optimisation of recycled rubber and performance of the product. The scope of this research in the preliminary stage included preparing mixes, which contained rubber up to 70% of the volume of initial fine aggregate. This task was performed by preparing samples contained verity of rubber content increasing by increment of 10%. Moreover, concrete mix series with water-cement (WC) ratios in the range of 0.35 to 0.55 were made with an increment of 0.05. Afterward, considering the producibility and the required properties for pavement concrete in the fresh state mix series with WC ratios of 0.40 and 0.45, and rubber content up to 40% were selected.

Based on the trial test results, rubber contents of 20% and 30% were found to be the practical content values and selected for introducing to the mix series with WC ratios of 0.45 and 0.40, respectively. Afterwards, ten mixes series (Table 3.8) for assessment of rubber treating with sodium hydroxide and water soaking method were prepared and presented as follows:

Table 3.8: Constituents for mix series prepared for assessing rubber treatment methods

Mix ID	Rubber treatment time	WC	Cement	Sand		Coarse aggregate		Rubber		Total
				Volume	Weight	10mm	20mm	Volume	Weight	
			[kg/m^3]	[%]	[kg/m^3]	[kg/m^3]	[kg/m^3]	[%]	[kg/m^3]	[kg/m^3]
0.45/00CR	No rubber	0.45	370	100	658	404	726	0	0	2325
0.40/00CR	No rubber	0.40	370	100	677	416	746	0	0	2356
0.45/20CR/24h[1]	24 hours	0.45	370	80	527	404	726	20	58	2251
0.40/30CR/24h	24 hours	0.40	370	70	474	416	746	30	89	2242
0.45/20CR/20m[2]	20 minutes	0.45	370	80	527	404	726	20	58	2251
0.45/20CR/7d[3]	7 days	0.45	370	80	527	404	726	20	58	2251
0.45/20CR/ARR	No treatment	0.45	370	80	527	404	726	20	58	2251
0.40/30CR/ARR[4]	No treatment	0.40	370	70	474	416	746	30	89	2242
0.45/20CR	Water soaking	0.45	370	80	527	404	726	20	58	2251
0.40/30CR	Water soaking	0.40	370	70	474	416	746	30	89	2242

[1] [WC ratio] / [crumb rubber content] / [method of treating rubber] (e.g. 0.45/20CR/24hr refers to a mix with WC of "0.45" and 20% of rubber which treated with NaOH for 24 hours),

[2] 20m represents 20 minutes of treatment, [3] 7d represents 7 days of treatment, [4] ARR represents untreated rubber

Table 3.9: Main mix series designations for unit volume of mix

Mix ID	WC	Cement	Sand aggregate		Coarse aggregate		Water	Rubber		WR	Total
			volume	weight	10mm	20mm		volume	weight		
		[kg/m^3]	[%]	[kg/m^3]	[kg/m^3]	[kg/m^3]	[kg/m^3]	[%]	[kg/m^3]	[l/m^3]	[kg/m^3]
M/0.40/00CR	0.40	370	100	677	416	746	148	00	00	3.196	2356
M/0.40/10CR[1]	0.40	370	90	609	416	746	148	10	30	3.990	2318
M/0.40/20CR	0.40	370	80	541	416	746	148	20	59	3.945	2280
M/0.40/25CR	0.40	370	75	508	416	746	148	25	74	4.052	2261
M/0.40/30CR	0.40	370	70	474	416	746	148	30	89	4.351	2242
M/0.40/40CR	0.40	370	60	406	416	746	148	40	118	4.443	2204
M/0.45/00CR	0.45	370	100	658	404	726	166	0	00	1.151	2325
M/0.45/10CR	0.45	370	90	593	404	726	166	10	29	1.225	2288
M/0.45/20CR	0.45	370	80	527	404	726	166	20	58	1.436	2251
M/0.45/30CR	0.45	370	70	461	404	726	166	30	86	1.554	2214
M/0.45/40CR	0.45	370	60	395	404	726	166	40	115	2.072	2177
M/0.50/00CR	0.50	370	100	640	393	706	185	00	00	-	2294
M/0.55/00CR	0.55	370	100	622	382	685	203	00	00	-	2263

[1] [mix type] [WC ratio] [rubber content] [method of treating rubber] M/0.40/10CR refers to "Main" mix with WC of "0.40" and 10% of rubber prepared with water soaking method.

The prepared thirteen sets (Table 3.9) of concrete can be classified in three categories. Firstly, mix series with WC ratio of 0.40 and rubber content of up to 40%. Secondly, mix series with WC ratio of 0.40 and rubber content up to 40%. Finally, the third array involved comparison of the results for samples, which were classified in the strength range of 32MPa for the 28-day characteristic compressive strength. This array covered three sets of the same strength samples, 0.40/25CR and 0.45/20CR and 0.50/00CR.

Further details on the properties of main mix series are discussed in Section 4.4 under the title of “Properties of Main Mix Series .”

3.3 Research Specifications and Test Methods

The Australian Standards (Austroad 2009) and NSW Standard (RTA R83 2010) signified the acceptable test results ranges for any concrete mix that can be used for concrete pavement. The fresh and hardened properties of all mix series were assessed based on the given acceptable ranges. Moreover, the prepared concrete was required to comply with the general requirements for the Normal grade 32MPa concrete. These additional requirements are addressed in the Australian Standards AS 1379 - Specification and supply of concrete (AS1379 2007) and need to be met for any normal grade concrete. The list of tests carried out for evaluation of fresh and hardened properties of the main mixes is presented in Table 3.10.

Table 3.10: The list of the conducted tests for the main mix series in this research

Test Name	Concrete Type	Standard No	Testing age or intervals
Slump	Fresh	AS 1012.3.1	Batching day
Compacting factor	Fresh	AS 1012.3.2	Batching day
Air content	Fresh	AS 1012.4.2	Batching day
Mass per unit volume	Fresh	AS 1012.5	Batching day
Bleeding	Fresh	AS 1012.6	Batching day
Compressive strength	Hardened	AS 1012.9	3, 7, 14, 21, 28 and 56 days
Flexural strength	Hardened	AS1012.11	7, 28 and 56 days
Elastic modulus	Hardened	AS 1012.17	7, 28 and 56 days
Fatigue test	Hardened	As explained in Section 3.3.5	56 days
Plastic shrinkage	Fresh	ASTM 1579	Batching day
Drying shrinkage	Hardened	AS 1012.13	up to 56 days (8 weeks)
Flexural toughness	Hardened	ASTM C1609	28 days
Modified toughness	Hardened	As explained in Section 3.3.8	28 days

In addition to the conducted fresh and hardened tests, the undertaken test program was extended to assess of any additional improvements gained in rubberised concrete. the additional tests included two major defects related to pavement concrete slabs, which are shrinkage and cracking. The requirements for the conducted tests are demonstrated in Table 3.11.

Table 3.11: Concrete pavement requirements and the conducted tests in this research

Test Name	Testing age	Criteria	Reference
Slump	Batching day	60±10 [mm]	(Austroad 2009; RTA R83 2010)
Compacting factor	Batching day	> 0.7[%]	(Neville & Brooks 2010)
Air content	Batching day	< 6.0 [%]	(Austroad 2009; RTA R83 2010)
Mass per unit volume	Batching day	2100-2800 [kg/m³]	(AS1379 2007)
Bleeding	Batching day	1.0-3.0 [%]	(RTA R83 2010)
Characteristic strength	28 days	>32.0 [MPa]	(Austroad 2009; RTA R83 2010)
Characteristic strength	7 days	>16.0 [MPa]	(AS1379 2007)
Flexural strength	28 days	>4.5 [MPa]	(Austroad 2009; RTA R83 2010)
Elastic modulus	7, 28 and 56 days	Checked for improvement	-
Fatigue test	56 days	Checked for improvement	-
Plastic shrinkage	Batching day	Checked for improvement	-
Drying shrinkage	21 days	<450 [µs]	(RTA R83 2010)
Flexural toughness	28 days	Checked for improvement	-
Modified toughness	28 days	Checked for improvement	-

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

3.3.1 Slump

Workability of fresh concrete is assessed using slump test. The aim of applying this test is explained in Section 2.2.1 entitled "Fresh Properties of Crumb Rubber ." This empirical method is elaborated by the Australian Standard AS1012.3.1 (AS1012.3.1 1998). The slump test is performed using a hollow frustum of a cone in a certain dimension, which is presented in in Figure 3.4

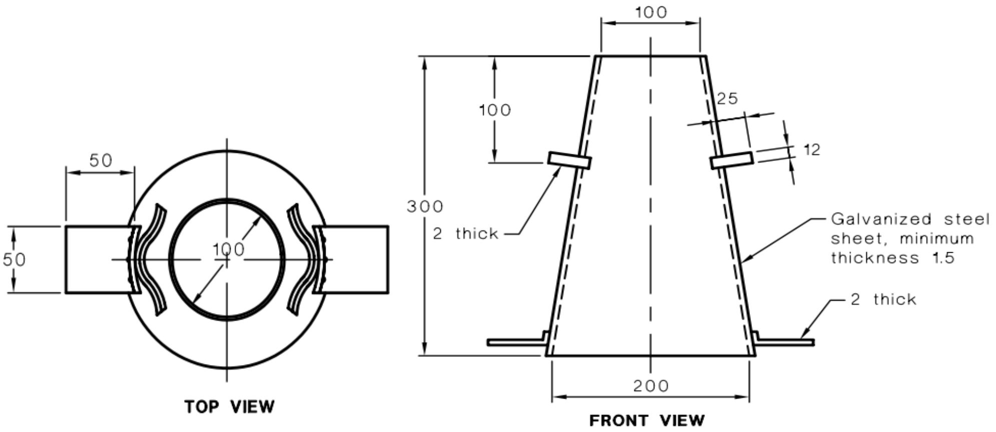


Figure 3.4: Typical mould used for the slump test (AS1012.3.1)

Specifications and standards showed that by performing the slump test, one of the four general forms of slump result might be resulted as shown in Figure 3.5. If slump shape of concrete evenly all rounds, it is called “true” slump. If one half of the cone slides down an inclined plane, it is termed a “shear” slump, which the slump test should be performed again.

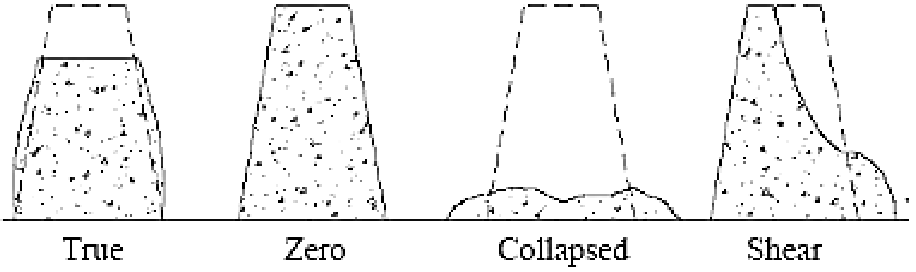


Figure 3.5: Schematic patterns for different types of concrete slump

It should be taken into account that if the shear slump persists, this characteristic is an indication of lack of cohesion. In addition, shear slump or collapsed mixes may suffer from segregation.

3.3.2 Compacting Factor

Degree of compaction is measured using compacting factor (CF). It can be performed by assessing of the ratio of concrete density for partially compacted concrete to the density of the same concrete which is fully compacted.

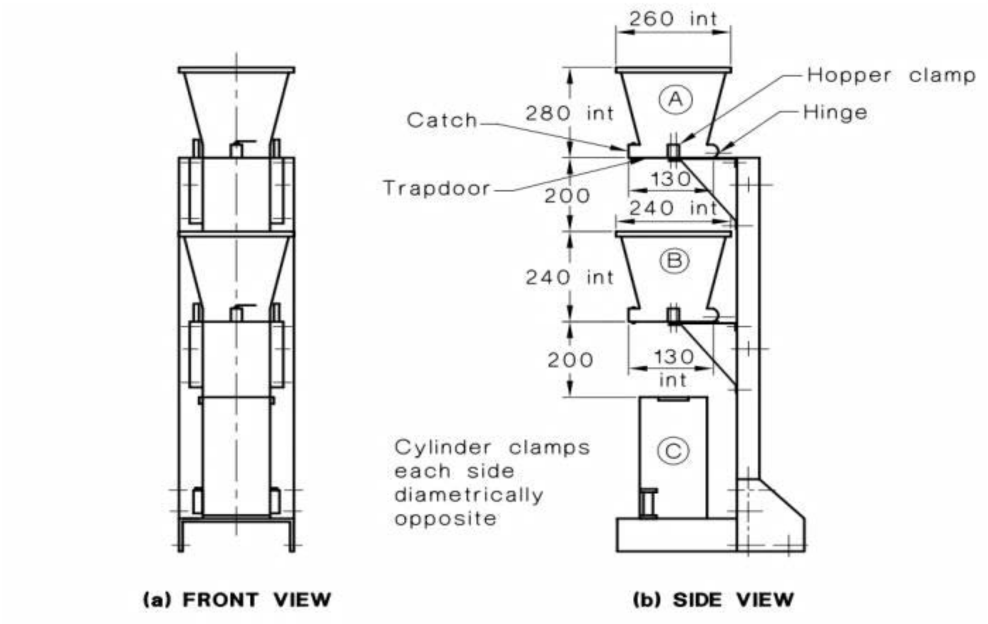


Figure 3.6: Standard compacting factor test apparatus (AS 1012.3.2)

Figure 3.6 demonstrates the standard apparatus for the test in accordance with the Australian Standard AS1012.3.2 (AS1012.3.2 1998). The results of this test can provide complementary information regarding the workability and compactability of prepared rubberised concrete in fresh state. The concrete compacting factor value may vary in a range between 0.78 (very low workability) to 0.95, which presents a high level of workability (Neville & Brooks 2010).

3.3.3 Air Content

The air content (AC) test is a method directly determines the air content of fresh concrete. It is carried out by the observation on the pressure gauge, which is calibrated to record the reduction of the air pressure in a predetermined test pressure applied to the concrete. Figure 3.7 demonstrates the typical test apparatus in accordance with the Australian Standard AS1012.4.2 (AS1012.4.2 1999) test procedure. There are different types of test methods available for measuring the AC of concrete. However, Standard AS1012.4.2 is considered as the most commonly used test method, because there is no need for performing extra calculations to achieve the AC of mix. The pressure gauge is calibrated to record the reduction in the pressure applied to the concrete, as the actual air content of the concrete.

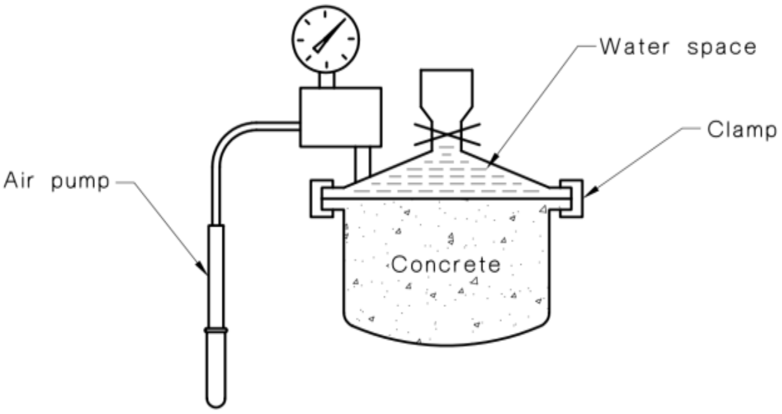


Figure 3.7: Typical apparatus used for measuring air content (AS 1012.4.2)

3.3.4 Mass per Unit Volume

Measurement of mass per unit volume (MPV) of fresh concrete is conducted by dividing the mass of fully compacted concrete in the measure by the capacity (volume) of the measure in the plastic state. The Australian Standard AS1012.5 describes the test procedure for measuring the concrete mass per unit volume. The Australian Standard

AS1012.5 (AS1012.5 1999) test procedure is applied for testing concrete with aggregates of nominal size not exceeding 40 mm, also the capacity of the measure should not be less than 5 litres. The volume of the measure is obtained by dividing the mass of water by the unit mass of water at testing ambient temperature.

3.3.1 Bleeding

The bleeding test carried out for determining the relative quantity of mixing water that will bleed from a sample of freshly mixed concrete under the conditions of the test. Measurement of bleeding of fresh concrete is conducted in accordance to the Australian Standard AS1012.6 (AS1012.6 1999). The Australian Standard AS1012.6 provides a relationship to quantify bleeding in a standard and consistent way. Considering only the amount of bleed water is not a proper way to compare mix arrays with different water-cement ratios and water contents, because this substantially affects the bleeding properties of concrete. According to the Standard AS1012.6 the "bleeding percent," can be calculated for different mix series, using the Equation (3.1).

$$Bleeding = \frac{V_1 \times M}{S \times V_2 \times 10} \times 100 \tag{3.1}$$

where V_1 is the quantity of bleed water in mL, M is total batch mass of concrete in kg, V_2 is the total volume of unbound water in mix in L, and S is mass of test specimen in kg

In order to conduct this test, a cylindrical container of approximately 0.015 m^3 capacity, and having an inside diameter of 250±3 mm and an inside height of at least 280 mm, shall be used. Then, the container should be filled with fresh concrete to the circumferential mark ±5 mm in approximately. The AS1012.6 procedure indicated that draw off water accumulated on the surface of concrete sample should be collected. It should be performed by using a pipette, or other devices, at 10 minutes intervals during the first 30 minutes. Subsequently, the draw off water should be measured at 30 minutes intervals, until the bleed water collected during 30 minutes periods is less than 5 mL.

3.3.2 Compressive Strength

Compressive strength test is considered an easy test to perform. Accordingly, this test is commonly applied on hardened concrete. Moreover, many of desirable characteristics of concrete are relied on its compressive strength. According to the Australian Standards AS1012.8 (AS1012.8.1 2000; AS1012.8.2 2000), testing method of concrete strength, cylindrical specimens were prepared to be tested for concrete compressive strength (Figure 3.8).

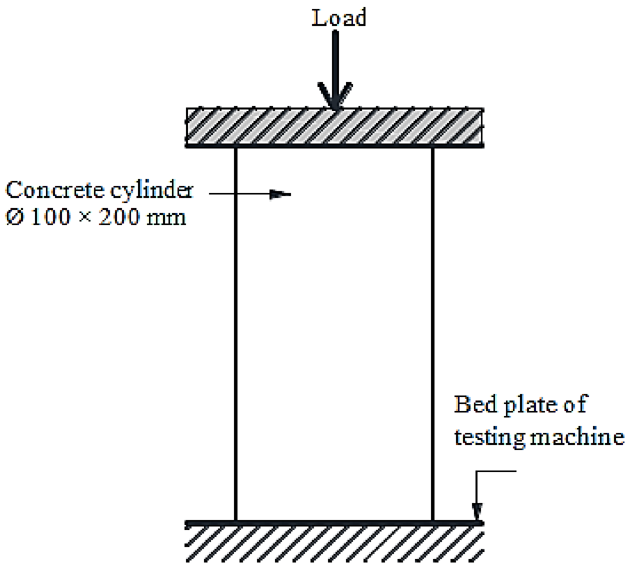


Figure 3.8: Schematic diagram of the compressive strength test

Afterwards, compressive tests were performed in accordance with the procedure of Australian Standard AS1012.9 (AS1012.9 2014). All the compressive tests were undertaken on cylindrical specimens of 100 mm diameter with 200 mm length. Prior to each test, concrete samples were properly capped. All tests were performed employing an 1800 kN universal testing machine used with load rate equivalent to 20±2 MPa per minute. Lastly, the compressive strength of the specimens was determined by dividing the maximum force that samples underwent, over the cross sectional area of samples. The compressive strength at the age of 28 days was measured for all samples, because the results of this test were required to be checked with the concrete pavement specification. In addition, as described earlier in Section 3.1.1, compressive tests were conducted on other ages for checking the effect of rubber addition on strength gaining of concrete mix with time. In order to achieve this goal additional tests carried out at the ages of 3, 7, 14, 21, and 56 days for samples with different contents of rubber.

3.3.3 Modulus of Rupture

In order to measure the tensile strength of rubberised concrete, the modulus of rupture test was conducted. The modulus of rupture (MOR) test involves subjecting an unreinforced concrete prism to a four-point flexural load until failure. The theoretical maximum tensile stress in the bottom fibre of the test specimen is known as the modulus of rupture that can be calculated on the basis of ordinary elastic theory presented in Equation (3.2).

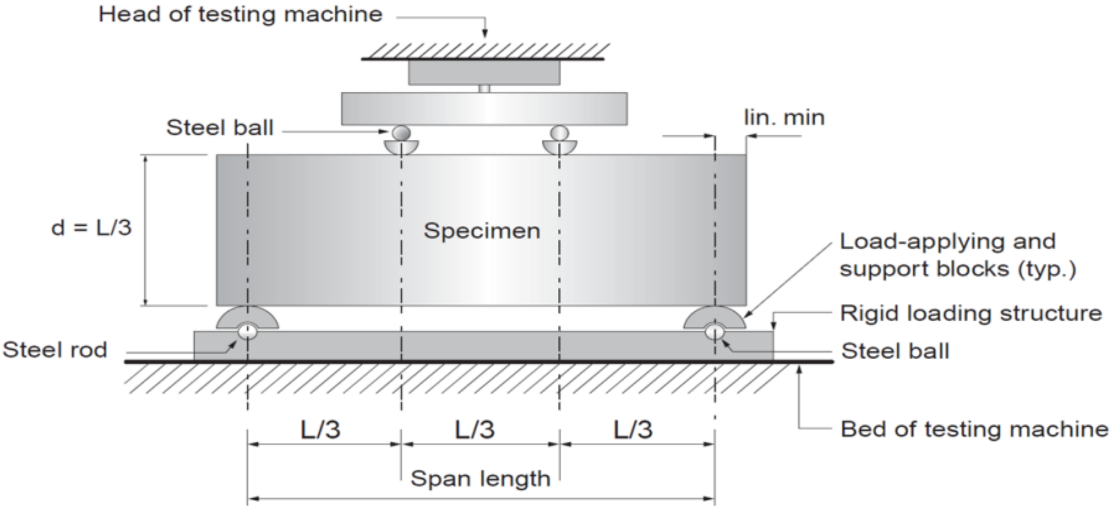


Figure 3.9: Typical arrangement for the Modulus of rupture test

Herein, the MOR is obtained from four-point bending tests on 100×100×350 mm prisms at a loading rate of 1±0.1 MPa/min until fracture, following the test procedure of the Australian Standard AS1012.11 (AS1012.11 2000). Four-point loading was applied and mid-span deflection of the flexural specimens is measured by means of a linear variable differential transformer (LVDT) at the centre of each specimen. Figure 3.9 shows the typical arrangement of 4-point bending test for concrete samples. The flexural stress is calculated as:

$$MOR \text{ or } f_{ctf} = \frac{PL \times 1000}{B \times D^2} \tag{3.2}$$

where MOR or f_{ctf} is the modulus of rupture in MPa, P is the maximum applied force in kN, L is span length in mm, 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.

Previous investigation by Raphael (1984) illustrated that the actual value of the tensile strength for concrete is estimated to be about 0.75% of the measured MOR values. The reason behind this phenomenon was described based on the actual shape of the stress block for the samples under the MOR test. It was found that the flexural strain was gradually increased with the increase in the cross sectional area about one-half of the tensile stress. Consequently, the shape of the actual stress block under loads adjacent to failure is parabolic and not triangular (Neville 2011).

3.3.4 Modulus of Elasticity

The Static chord modulus MOE is defined as a gradient of the chord drawn between two specific points on the stress-strain curve according to the Australian Standard AS1012.17. The Australian Standard AS1012.17 (AS1012.17 1997) addressed these two points and the required data, which should be recorded as follows:

a) Point g_1, where the measured strain is 50 micro-strains and the corresponding stress to this strain

b) Point g_2, 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 ring, presented in Figure 3.10, was used.

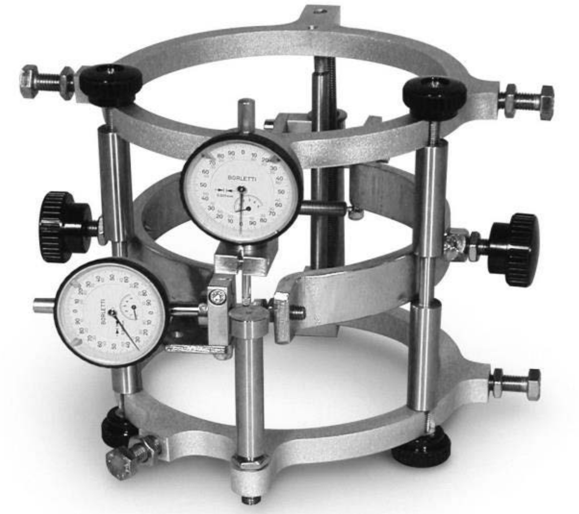


Figure 3.10: The compressometer arrangement for measuring the longitudinal strain

Test is conducted under a load rate control condition in an 1800 kN universal testing machine with load rate equivalent to 15±2 MPa per minute.

Accordingly, the MOE of the concrete sample can be calculated as follows:

$$E_c = \frac{G_2 - G_1}{\varepsilon_2 - 50 \times 10^{-6}} \tag{3.3}$$

where E_c is the concrete modulus of elasticity in MPa, G_2 is the test load (as described above), divided by the cross-sectional area of the specimen in MPa, G_1 is the applied load at a strain of 50×10^{-6} divided by the cross-sectional area of the specimen in MPa and ε_2 is the strain corresponding to deformation at test load in microstrain.

3.3.5 Cyclic Loading (Fatigue)

The application of the cyclic flexural loading test was introduced on prismatic samples by Pindado et al. (1999). The cyclic load was applied on the samples in lower stress level that the maximum stress that they could carry (Lee & Barr 2004; Hernández-Olivares et al. 2007). In order to perform the flexural fatigue test, a similar setting to the flexural test, applied to the 56-day water cured concrete samples. The applied loading pattern is shown in Figure 3.11.

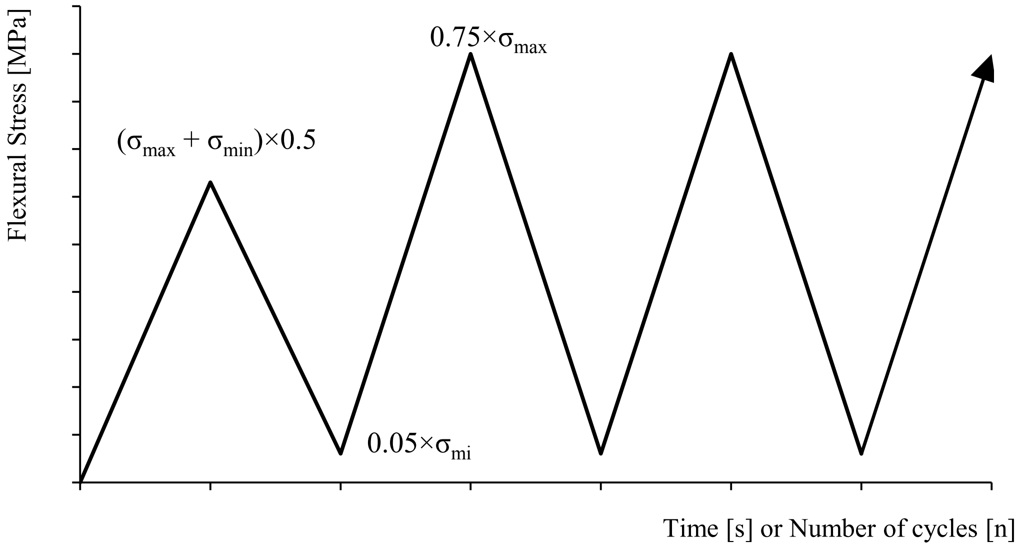


Figure 3.11: The loading pattern of cyclic test, (after Pindadoet al. 1999)

Based on the results of MOR test conducted at the age of 56 days, the maximum flexural stress ($\sigma_{\max}$) of samples were determined. Then, a cyclic load with the minimum of $0.05\sigma_{\max}$ and maximum of $0.75\sigma_{\max}$ applied to all samples. Literature indicated that the minimum $0.05\sigma_{\max}$ is required to be kept on the samples when they are unloaded in cyclic test. This minimum stress prevents any detachment of sample from the testing machine during the test. The mentioned detachment results in an impact load on sample leads to a biased result. It was observed that none of the samples failed after applying of 1000 cycles of the described cyclic load. Due to the limitations dominated by the testing machine, the repetition of the testing cycle was limited to the 1000 cycles. Consequently, samples were subjected to a new stronger cyclic load with a minimum of $0.05\sigma_{\max}$ and a maximum of $0.9\sigma_{\max}$. Accordingly, samples which can resist more cycles are considered to have a better performance regarding the fatigue damage. The outcomes of this test are discussed in Section 4.4.2.

3.3.6 Plastic Shrinkage

There is no specific Australian test method available for carrying out investigation regarding early-age plastic shrinkage. In the past several decades, many experimental techniques have been proposed for studying plastic shrinkage cracking. Reviewing the literature the proper plastic shrinkage test method was selected. The Standard ASTM C1579 test was found to be the most suitable test, because the Standard ASTM C1579 test setting considers the concept of plastic shrinkage from one hand, and the condition that the restraining friction of subbase applying to concrete pavements on the other hand. The samples geometry (560×355×100 mm) provides sufficient restraint at the base of the slab through the base grips, while a stress riser placed in the centre of the slab significantly reduces the slab thickness.

Crumb rubber concrete was assessed regarding the effects, which incorporation rubber may have in controlling plastic shrinkage cracks. The plastic shrinkage tests were conducted in accordance with the Standard ASTM C1579. The prepared sets of concrete were casted into the prepared moulds, then screeded and finished with a trowel in accordance with the Standard ASTM C1579. According to ACI 305R-99 evaporation rates greater than 0.25 $kg/m^2/hr$, the exposed concrete surface results in plastic cracking (Neville & Brooks 2010). However, the requirement for conducting plastic shrinkage test in accordance with the Standard ASTM C1579 is the evaporation rate of over 1 $kg/m^2/hr$, which was provided for test samples in this research. The rate of evaporation can be predicted initially based on the formula provided based on the ACI nomograph (Kalousek 1954):

$$E = 5 \times \left([T_c + 18]^{2.5} - RH \times [T_a + 18]^{2.5} \right) \times (V + 4) \times 10^{-6} \tag{3.4}$$

Where E is evaporation rate in kg/m²/h, T_c is concrete (or water surface) temperature in °C, T_a is the air temperature in °C, RH is the relative humidity in percentage and V is the wind velocity in kilometer per hour

The special chamber was prepared for the samples in order to keep them in the testing standard condition for 24 hours after the casting. Samples were put into the chamber after finishing within a time interval less than 30 minutes after start of concrete mixing. The prepared chamber provided the ambient conditions of 36°C±3°C for the temperature and the proper relative humidity of 30%±10% and wind velocity of 5±1 m/s. Cracks are expected to occur above the stress riser and across the width of the specimen. By quantifying the crack properties of differently rubberised samples, the effect of adding rubber into concrete mix can be quantified.

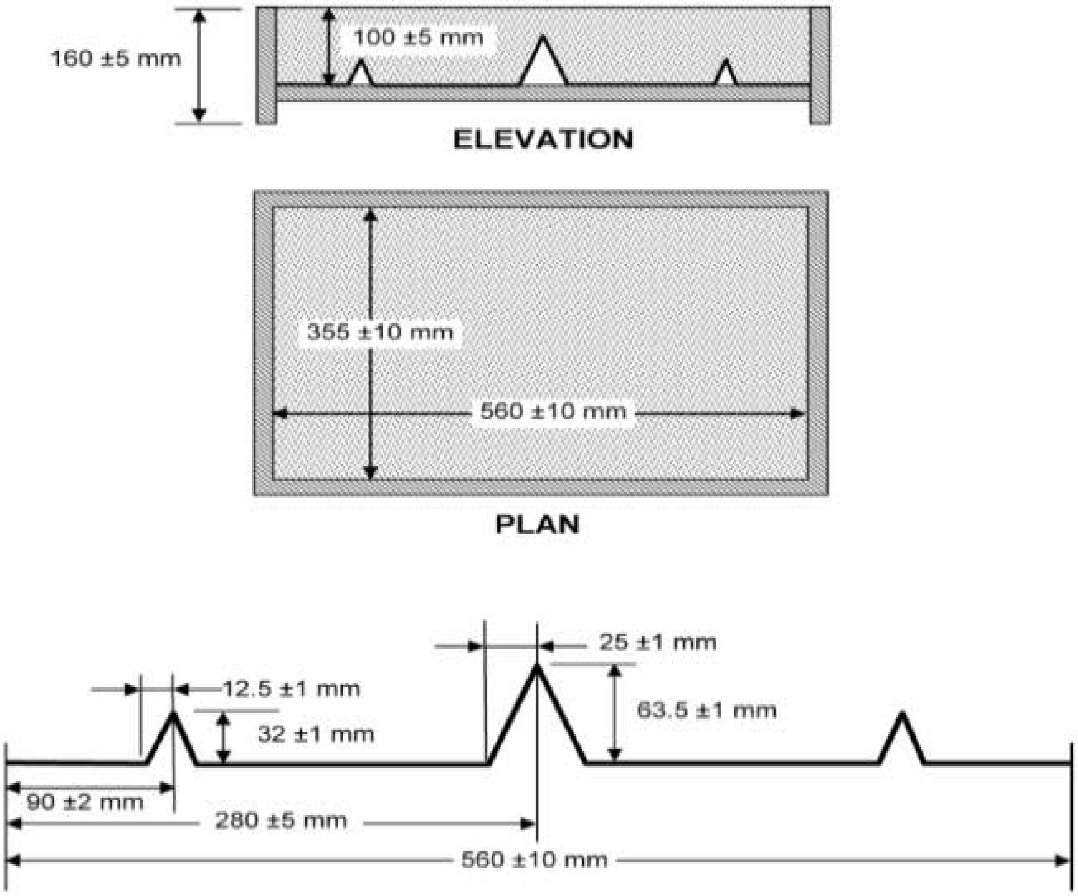


Figure 3.12: Early-age plastic shrinkage testing box (ASTM C1579)

Two specimens with a volume of approximately 18 litres prepared from each batch of concrete, and then samples were put into the conditioning chamber. Then, specimens were taken out of the environmental chamber after 24h±2h.

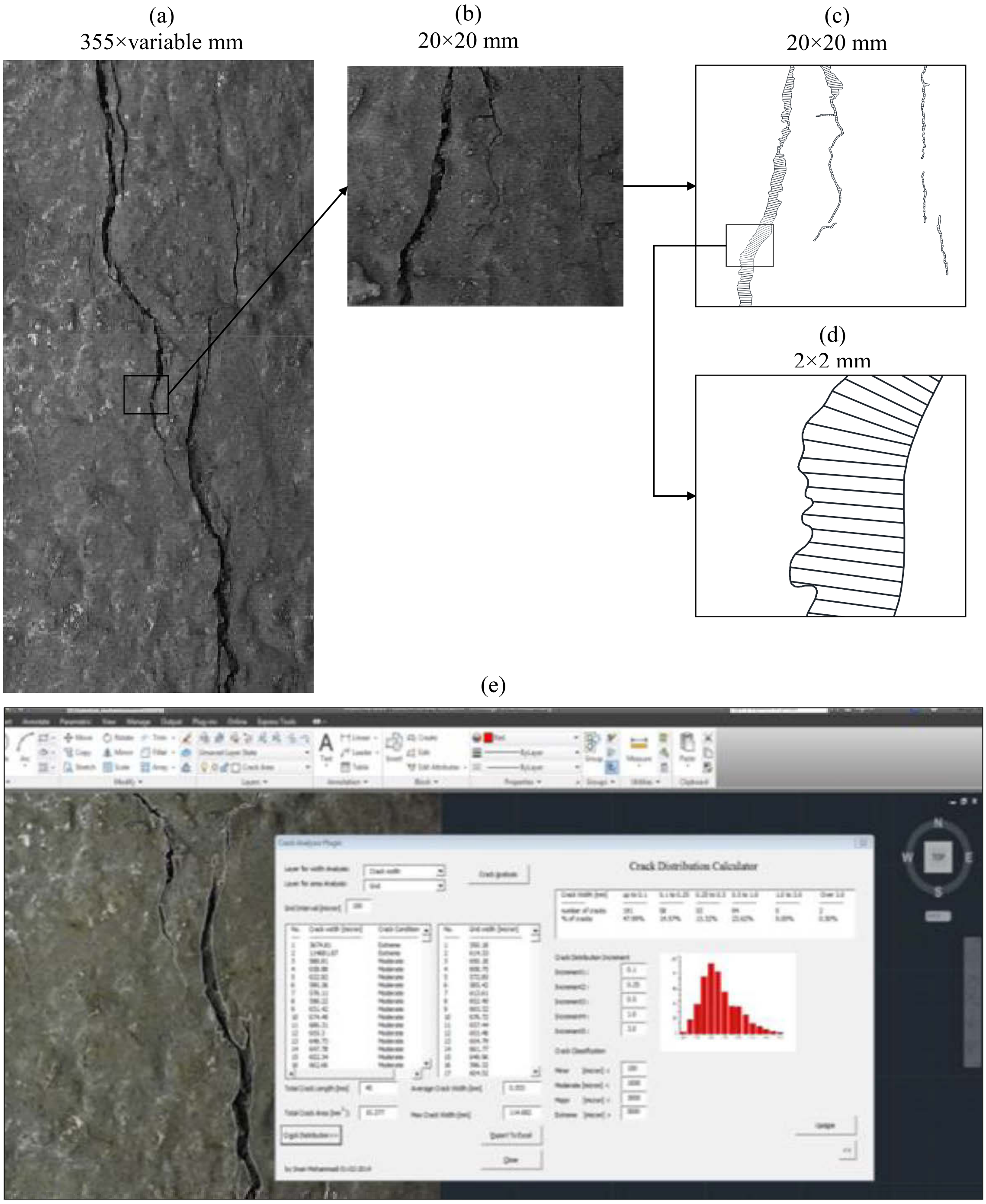


Figure 3.13: (a, b, c and d) process of quantifying the cracks on the surface of samples, (e) the interface of the VBA plug-in running on an AutoCAD software platform

As can be seen in Figures 3.13 (a) and (b), a series of images in the size of 20×20 mm were taken from the cracks on the surface of samples. These high resolution images were taken from the same height of 100 mm with the accuracy of around eight megapixels. Subsequently, pictures were imported into AutoCAD software, then scaled and analysed based on the procedure presented in Figures 3.13 (c) and (d). This task conducted by setting the boundary of cracks in software, and then a set of grids with spacing of 100 microns created over each crack, which is presented in Figure 3.13(d). The created grids were set in a perpendicular direction to the paths that cracks were propagated.

The applied method provided essential data regarding crack analysis, which involved crack widths, lengths and area for each concrete sample. In order to provide a systematic method for quantifying the shrinkage cracking of concrete, a piece of sophisticated code written in VBA programming langue, which could be run on an AutoCAD platform was used As shown in Figure 3.13(e). The introduced advanced image analysis technique provided a reliable and consistence assessment for quantifying the plastic shrinkage cracks.

The codes programmed for this research enabled generating grids to consider the actual crack paths. Qi (2003) generated series of horizontal grids for processing cracks images. However, the generated grids in this research were perpendicular to the cracks paths and significantly improved the accuracy of results, specifically for measuring shrinkage crack widths.

3.3.7 Drying Shrinkage

This test is performed on prisms specimens with dimension of 75×75×280 mm prepared in accordance with the Australian Standard AS 1012.13 (AS1012.13 1992) (Figure 3.14). Drying room prisms kept in drying room with suitably controlled temperature, humidity and air circulation shall be provided for storing specimens in air.

The temperature in the drying room shall be maintained at 23±1°C for 90% of each 24 h period, at all times remaining within the range 23±2°C and the relative humidity in the drying room shall be maintained at 50±5% at all times. Samples are cured for seven days in saturated lime and then in drying room. The change in length and weight of samples are measured in the appropriate time after total periods of air drying of 7, 14, 21, 28 and 56 days.

Figure 3.14: Drying shrinkage (AS 1012.13) setting, (a) moulds and (b) measurement setting

3.3.8 Toughness

ASTM C1609 test was selected to be conducted for evaluating the flexural performance and the residual flexural tensile strength of rubberised concrete. This test applies parameters derived from the load-deflection curve, which can be obtained by testing a simply supported beam under third-point loading system (Figure 3.15).

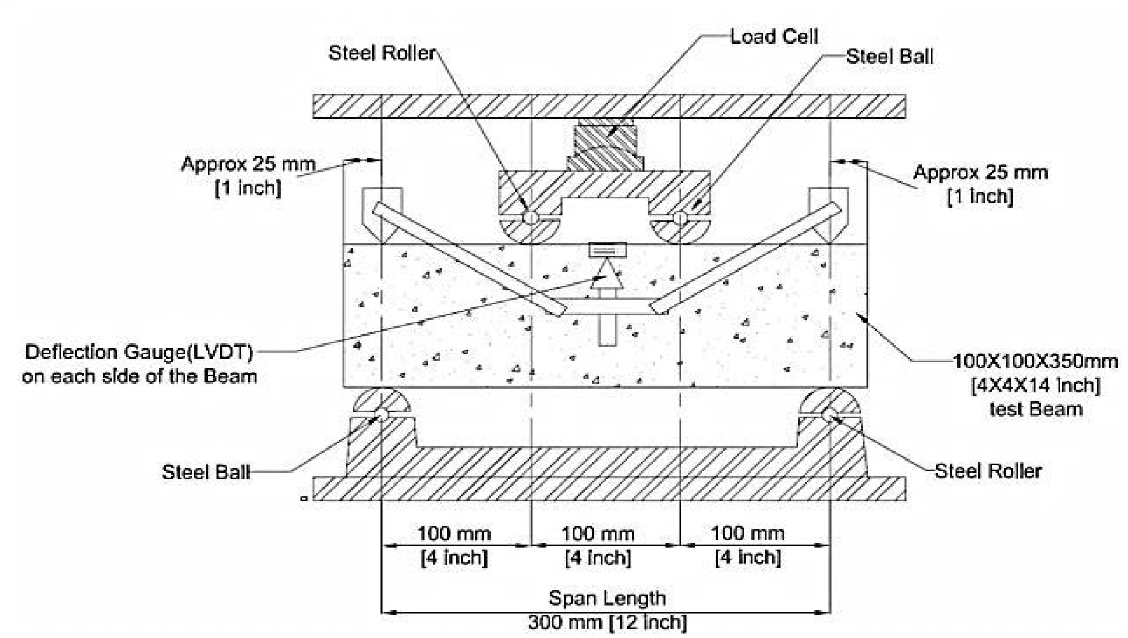


Figure 3.15: Typical arrangement of 3rd point bending test (ASTM C1609)

Due to lack of a proper test method, which can be conducted in accordance with the Australian Standard, the ASTM C1609 test was selected. The specimens used for the test are 100×100×350 mm prisms prepared in accordance with the test procedure.

From the results of 3rd point bending test over prisms at the age of 28 days, the load-deflection chart can be plotted as shown in Figure 3.16. Calculation for peak strength using the following formula:

$$f_1 = \frac{p \times l}{b \times d^2} \tag{3.5}$$

where f_1 is the flexural strength in MPa, P is the load in N, l is the span length in mm, b is the average width of the specimen in mm and d is the average depth of the specimen in mm.

It is required to calculate the equivalent flexural strength ratio $R^D_{T,150}$ according to Equation (14) using the peak strength and the toughness, T^D_{150}, which is calculate as the total area under the load-deflection curve up to a net deflection of l⁄150 of the span length.

$$R^D{}_{T,150} = \frac{150 \times T^D{}_{150}}{f_1 \times b \times d^2} \times 100\% \tag{3.6}$$

where f_1 is the peak flexural tensile strength, T^D_{150} is the total area under the load-deflection curve up to a net deflection of l/150 and b and d are samples dimensions.

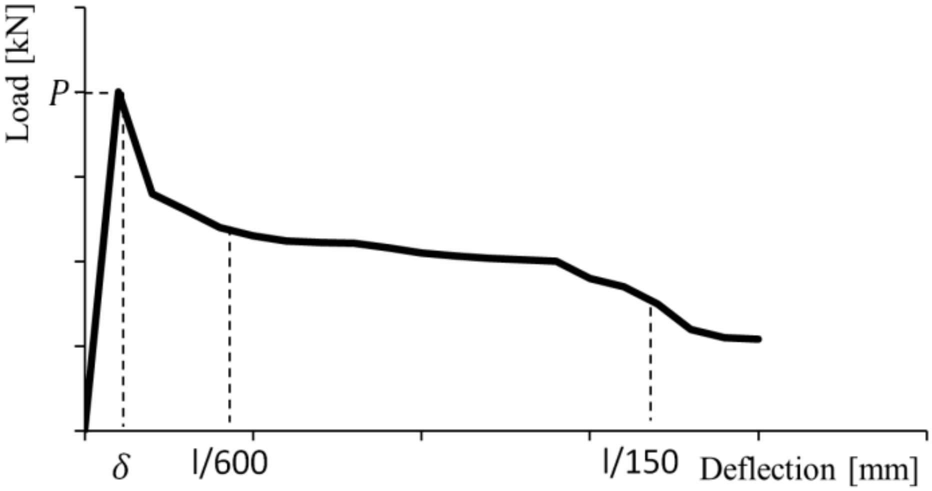


Figure 3.16: Typical load-deflection chart (ASTM C1609)

After the toughness tests were accomplished, conducting the modified toughness test procedure was also trialled. Recently, in an investigation on fibre reinforced concrete it was suggested to conduct ASTM C1609 test in lower rate of loading. Islam (2012) introduced a method used the same setting but applied 25 times lower loading rate compared to the Standard ASTM C1609. Using this method took longer time but sudden failure of specimen, which occurs due to high initial loading rate, can be avoided. It is reported that test results were more consistent at lower loading rate. Although Islam (2012) applied a loading rate in average 25 times lower than the Standard ASTM1609, in this research the loading rate was reduced only 10 times.

The selected rate was not as low as suggested by Islam (2012) due to some technical limitations regarding the testing machine. The absence of any significant difference between the results of standard test and the results of modified test proved that lowering the loading rate of the standard test is not beneficial for rubberised concrete. In contrast, lowering the loading rate made the test very time-consuming and difficult to be performed. Table 3.12 shows a comparison of the applied methods.

Table 3.12: Standard ASTM1609 toughness test description and comparison

Test type	Selected Loading rates		Results and consideration	Recommendation
	d<L/900 [mm/min]	d>L/900 [mm/min]		
ASTM1609 Standard test	0.025-0.075	0.20	Results are shown in Section 4.4.2	Suggested to be carried out for future investigation on rubber modified concrete
ASTM1609 modified test	0.005	0.02	Conducting test was time-consuming. The results were same as the standard test	Not recommended to be carried out.
ASTM1609 modified by Islam (2012)	0.001	0.02	Test was not practical carrying out each set of tests took more than 24 hours	Not recommended to be carried out.

Chapter 4

Results and Discussion

4.1 Introduction

This chapter demonstrates and compares the experimental results. Firstly, the valid ranges for different variables involved in this research were investigated. The appropriate ranges of water-cement ratio (WC), rubber content and Water-Reducer (WR) were set according to the results of the conducted trial tests. Afterwards, different treating methods of rubber were examined. Then, arrays of samples were prepared for assessing the mechanical and shrinkage properties of rubberised concrete. Lastly, the change of concrete properties based on the change of different variables were indicated and discussed.

4.2 Trial Mix Series

Mixing rubber into concrete mix is a critical issue regarding the content of concrete constituents. Fibres, additives or admixtures or other modifiers, which occupy a low portion (roughly <5%) of the total volume of the concrete mix. unlikely, introducing rubber into the concrete mix, strongly affect the mix proportioning. However, some studies (Ganjian et al. 2009; Sukontasukkul 2009; Khorrami et al. 2010; Taha et al. 2009; Kaloush et al. 2005) in the field of rubberised concrete have not taken into account the accurate nature of this modification. It can be considered as a source of error if the replacement of aggregates with rubber is conducted based on the aggregates weight. The specific weight of aggregate in the concrete mix is roughly 2.5 times greater than rubber. Therefore, the same weight of the substituted rubber occupies 2.5 times higher volume compared to the replaced aggregate in the mix. Any replacement considering the weight of aggregate leads to a wrong mix proportioning, which is not adjusted for one cubic metre. This study aims to highlight the requirements for any replacement of aggregates with rubber based on the volume of aggregates instead of the aggregates weight for any future studies in the field of rubberised concrete.

Series of trial mix were prepared in order to verify the applicability of the selected ranges for the water-cement (WC) ratio and the crumb rubber content. The principal aim of trailing mix was to assess the overall properties of crumb rubber concrete (CRC) before making main batches. The trial mix, shown in Table 3.7, were prepared for WC ratios ranging from 0.35 to 0.55 and the rubber content up to 70% by the volume of fine aggregate. Due to the high concentration of rubber in the mix containing 50, 60 and

70% of rubber the prepared samples from these mixes were found not to be homogenous. Moreover, the difficulty associated with compacting of CRC prepared with a high concentration of rubber was revealed, and consequently the replacement rubber with aggregate was limited up to the 40% content.

The trial mixes were only tested for characteristics necessary to start proportioning the design batches. Extra WR was added to all trials even after reaching the 60mm slump target. This was performed in order to evaluate the concrete response and its sensitivity to the selected WR Plastiment10. Based on data demonstrated in Table 4.1, there were some issues associated with the rubberised mix prepared with WC ratios of 0.35, 0.50 and 0.55. Two additional trial mixes were prepared for rubber content of 20% and WC ratios of 0.50 and 0.55. Trial results indicated that introducing rubber to a mix containing high volume of water was not applicable because these types of mixes were highly sensitive to applying vibration forces. In addition, they were very problematic to be compacted. It was observed that the rubber particles tended to float on the top of the mix. Thus, for these mixes no fresh tests were performed and mixes were rejected initially.

Trialled rubberised mixes prepared with 0.35 WC ratio showed low workability. In order to achieve target slump of 60 mm for rubberised concrete prepared with WC ratio 0.35, adding high volume of WR was required. It resulted in shear collapse of mix for rubberised mix in slump test. Moreover, the required dosage of WR for WC ratio of 0.35 was out of the acceptable range of admixture, specified by the Australian Road Authority guides (Approved Supplier List 2013). Mixes with WC ratios of 0.40 and 0.45 did not have any major issues in achieving the required slump of 60±10 mm using WR. It was found that the slump of 60mm can readily be achieved by adjusting the mix WR content.

Introducing more water-reducer into mixes with water-cement ratios of 0.40 and 0.45 resulted in the true slump numbers over 100 mm without any collapse or shear, and showed a satisfactory level of cohesiveness for the prepared mix. Segregation was only observed in case of addition of too much WR into the mix at the slump numbers of 150 mm and more (these slump numbers were two times greater than the required 60 mm slump number for concrete pavement).

Table 4.1: The test results of the prepared trial mixes

Mix ID	Rubber Content [%]	WC	WR [mL/m^3]	Slump [mm]	Type of slump	Stability of Slump	AC [%]	MPV [kg/m^3]
T/0.45/00CR[1]	00	0.45	0	35	True	Yes	-	-
T/0.45/00CR	00	0.45	1,110	55	True	Yes	1.4%	-
T/0.45/00CR	00	0.45	2,220	100	True	Yes	-	-
T/0.45/00CR	00	0.45	3,330	200	Collapse slump	No[1]	0.8%	2,470
T/0.45/20CR	20	0.45	0	30	True	Yes	-	-
T/0.45/20CR	20	0.45	1,110	50	True	Yes	2.4%	-
T/0.45/20CR	20	0.45	2,220	90	True	Yes	-	-
T/0.45/20CR	20	0.45	3,330	180	Collapse slump	No	1.9%	2,350
T/0.45/40CR	40	0.45	0	15	True	Yes	-	-
T/0.45/40CR	40	0.45	1,110	30	True	Yes	5.9%	-
T/0.45/40CR	40	0.45	2,220	70	True	Yes	-	-
T/0.45/40CR	40	0.45	3,330	170	Collapse slump	No	4.4%	2,150
T/0.35/00CR	00	0.35	2,960	0	No Slump	Yes	-	-
T/0.35/00CR	00	0.35	5,920	35	True	Yes	-	-
T/0.35/00CR	00	0.35	7,400	85	True	Yes	1.9%	-
T/0.35/00CR	00	0.35	8,880	170	Collapse slump	No	1.2%	2,500
T/0.35/20CR	20	0.35	2,960	0	No Slump	Yes	-	-
T/0.35/20CR	20	0.35	5,920	25	True	Yes	-	-
T/0.35/20CR	20	0.35	7,400	45	Collapse slump	No	3.2%	-
T/0.35/20CR	20	0.35	8,880	160	Collapse slump	No	1.6%	2,400
T/0.35/40CR	40	0.35	2,960	0	No Slump	Yes	-	-
T/0.35/40CR	40	0.35	5,920	15	True	Yes	-	-
T/0.35/40CR	40	0.35	7,400	45	True	No	6.2%	-
T/0.35/40CR	40	0.35	8,880	140	Collapse slump	No	1.7%	2,340
T/0.40/00CR	00	0.40	1776	35	True	Yes	-	-
T/0.40/00CR	00	0.40	2960	55	True	Yes	1.5%	-
T/0.40/00CR	00	0.40	4144	85	True	Yes	-	-
T/0.40/00CR	00	0.40	5328	160	Collapse slump	No	1.0%	2,426
T/0.45/50CR	50	0.45		Rejected before accomplishing fresh tests				
T/0.45/60CR	60	0.45		Rejected before accomplishing fresh tests				
T/0.45/70CR	70	0.45		Rejected before accomplishing fresh tests				
T/0.50/00CR	20	0.50		Rejected before accomplishing fresh tests				
T/0.55/00CR	20	0.55		Rejected before accomplishing fresh tests				

[1] Washed out aggregates, segregation and lack of cohesiveness observed

The mix with a water-cement ratio of 0.35 needed too much water-reducer (WR) admixture, to comply with the workability requirement. It was observed that addition of too much WR caused segregation in the mix resulted in the reduction of mix cohesiveness. On the contrary, avoiding the addition of the required WR resulted in the loss of workability (Figure 4.1 (a)). Addition of too much WR caused a lack of cohesiveness and resulted in a mix with washed out and disintegrated aggregate as shown in Figures 4.1 (b) and (c).

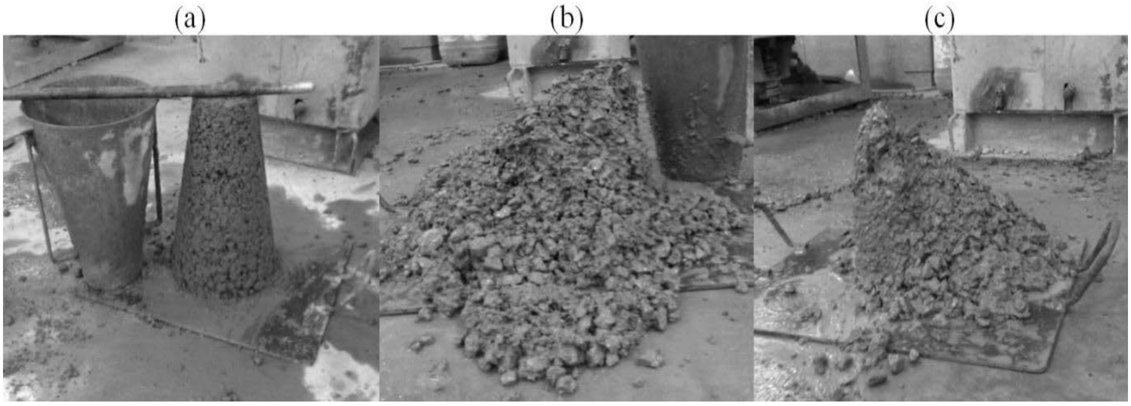


Figure 4.1: WC=0.35 (a) zero-slump for mix, which was not workable, (b and c) introducing of WR admixture, resulted in shear-slump, segregation and lack of cohesiveness

The segregation in trials prepared by WC=0.35 resulted in rejection of test series with this WC ratio. Moreover, the required dosage of WR was out of the acceptable range of admixture, specified by the Australian Road Authority guides (Approved Supplier List 2013). Mix series with WC ratios of 0.40 and 0.45, shown in Figure 4.2, did not have any major issues in achieving the required slump of 60±10 mm using WR. It was found that the slump of 60 mm can readily be achieved by adjusting the mix WR content.

Figure 4.2: WC =0.45 (a) adjusted to the slump of 60±10 mm, (b) addition more WR caused a higher slump up to 100 mm without segregation, shear or collapse slump

Introducing more WR into mix series with WC ratios of 0.40 and 0.45 resulted in the true slump numbers over 100mm without any collapse or shear, and this showed a satisfactory level of cohesiveness for the prepared mix series. Segregation was only observed in the case of addition of too much WR into the mix at the slump numbers of 150 mm and more (these slump numbers were two times greater than the required 60 mm slump number for concrete pavement).

Finally, WC ratios of 0.40 and 0.45 were selected to be investigated in the next stage of this investigation. The measured air content varied in the range of 1% to 6%, which meant using defoamer for reducing the air content, was not required. The resulted mass per unit volume (MPV) was in the range of 2150 to 2500 kg/m³; therefore, the prepared rubberised concrete was not classified as lightweight concrete.

Table 4.2: Comparison of trial mix test results with the concrete pavement criteria

WC	Target Slump	Ac[%]	MPV[kg/m³]	Observation result	Results
0.35	Not achievable	1.9-6.2	2,340-2,500	Segregation & lack of cohesiveness	Rejected ×
0.40	Achievable	1.5	2,426	Satisfied pavement concrete criteria	Accepted ✓
0.45	Achievable	1.4-5.9	2,150-2,470	Satisfied pavement concrete criteria	Accepted ✓
0.50	Not compactable	-	-	Not homogenous mix	Rejected ×
0.55	Not compactable	-	-	Not homogenous mix	Rejected ×

The results of trial mix series in Table 4.2 show that the 40% of CR content is a valid upper bound for introducing crumb rubber into the concrete mix. Replacement of more than 40% of fine aggregate with rubber should be avoided, because it increases the possibility of occurring reduction in homogeneity of the mix, resulting nonuniform distribution of rubber particles throughout the prepared concrete mix.

4.3 Treatment of Rubberised Concrete

Although a considerable amount of research has been conducted so far on the concept of using recycled rubber in cementitious composites (e.g. Ho et al. 2009; Bewick et al. 2010), very limited studies have been performed on mixing and treatment methods that improve the mechanical behaviour of crumb rubber concrete (CRC).

4.3.1 Water-Soaking Method of Adding Rubber into Mix

This study investigates the effect of a soaking rubber as expresses earlier in Chapter 3. It involves evaluation of the method of wet addition of crumb rubber into the concrete mix series by conducting tests regarding the generic mechanical properties of CRC. The introduced method of "water soaking" is cost effective and practical for making a homogenous mix, that rubber particles are evenly distributed. Moreover, this method results in the formation of better bond between rubber and cement paste in concrete.

Introduction of Water-Soaking Treatment

There are some difficulties such as lack of homogeneity and reduction of strength have been reported in the literature, when rubber is introduced into the concrete mix (John & Kardos 2011; Turatsinze & Garros 2008; Jingfu et al. 2008; Ho et al. 2009). These problems are the result of the major difference between volumetric properties of rubber particles and concrete aggregates. Rubber products have a specific gravity (SG) of 1 approximately, while concrete aggregates and cement paste have SG of 2.6 and 2.2, respectively. As a consequence, making a uniform and homogeneous mix containing rubber possibly is a difficult task. Moreover, rubber particles entrap high volume of air bubbles into concrete (Kaloush et al. 2005), which is not preferable. In addition, it was reported that the bond between rubber particles and the cement paste is weak (Turatsinze et al. 2006; Khorrami et al. 2010; Pacheco-Torgal et al. 2012), and consequently, some researchers attempted to improve the bond between rubber and paste (Ho et al. 2009; Segre et al. 2002; Zheng et al. 2008). This study introduces a new effective way of rubber incorporation into concrete to diminish these difficulties.

Majority of the previous studies on rubberised concrete involves introducing rubber into the concrete mix, in the same way of concrete aggregate without any special consideration. However, limited studies introduced a number of methods, which can be classified as the most commonly improving methods of mixing rubber with concrete.

Applications of these methods are expensive, and also the outcomes have not been consistent for different studies. Some studies applied chemical treatment of rubber with chemical solutions, such as acid or alkali solutions (Balaha et al. 2007; Pelisser et al. 2011; Youssf & Elgawady 2013; Siddique & Naik 2004; Pacheco et al. 2012). Other treatment methods including the use of pozzolanic or other special cementitious constituents, such as silica fume (Pelisser et al. 2011; Balaha et al. 2007) or magnesium cement (Biel et al. 1996), which may lead to the formation of a better adhesion between rubber and paste, were examined previously.

The major problem associated with the direct addition of rubber into the concrete mix is the tendency of rubber particles to trap air bubbles, which are attached to them. Disintegration of rubberised mix series might be more intense if the produced mix undergoes severe vibration during compaction time. Over-vibration of rubberised sample does not increase the level of compaction. In contrast, it results in segregation of mix mainly by moving rubber particles to the surface layer of the mix. Principally the source of this behaviour is found relies on three main reasons. The water-repelling (Youssf & Elgawady 2013; Siddique & Naik 2004) behaviour of rubber particles, which termed as hydrophobic characteristic of rubber.

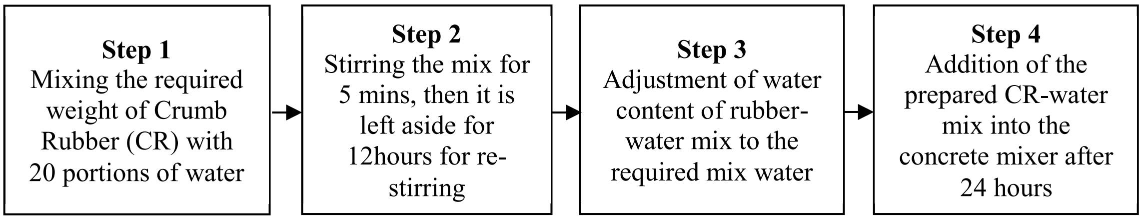


Figure 4.3: Wet procedure of introducing water soaked rubber into concrete mix

Secondly, the difference between the specific gravity of rubber particles and other mix elements, and finally the entrapped clinked air bubbles to rubber particles, which make the combination of rubber and air bubble relatively much lighter than other concrete constituents.

Using the introduced method in this study, the rubber surface is not only washed and cleaned with water, but also kept soaking in a container of water for 24 hours. Applying the introduced method can significantly resolve the above mentioned problems. During the period of 24 hours of water-soaking the trapped air bubbles, which are attached to rubber particles can get enough time to release gradually and the observed rubber hydrophobic behaviour can significantly be resolved. The introduced procedure is required to be commenced 24 hours prior to mixing as presented in Figure 4.3.

It was observed that just after addition of rubber to the container of water most of the particles (roughly over 50% of rubber particles) were floating on water, but gradually after 24 hours most of them were sunk to the bottom of the container (Figure 4.4).

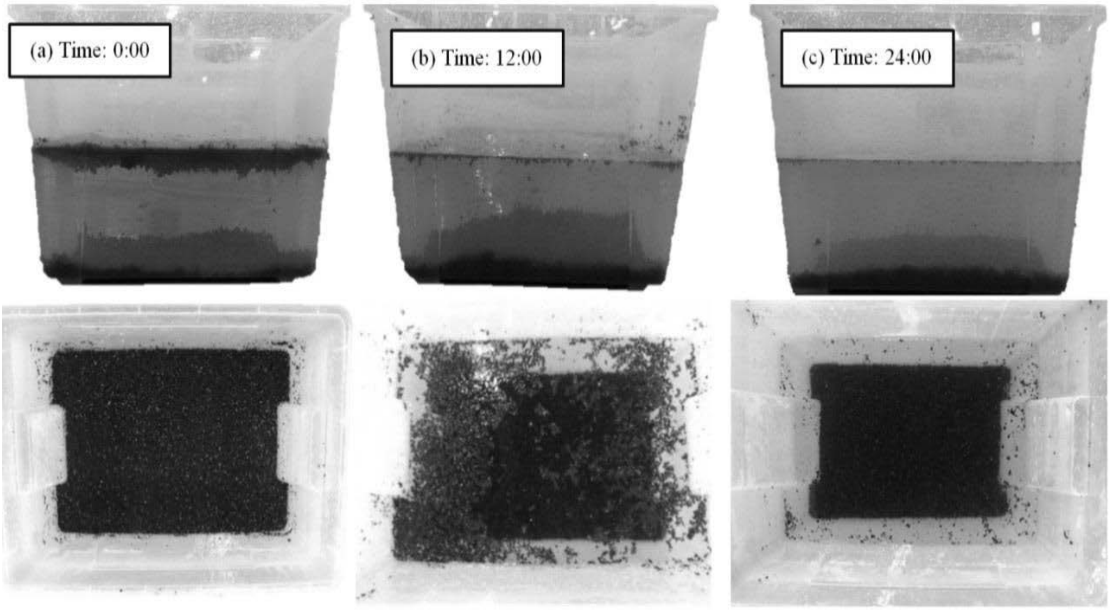


Figure 4.4: Stages of preparation water soaked treated rubber (a) just after mixing 50% of CR particles are floating, (b) after 12 hours 5% of crumb rubber is floating, (c) after 24 hours less than 1% of crumb rubber is floating

In addition, the effect of soaking rubber for 24 hours is demonstrated in Figure 4.5. It can be seen from Figure 4.5 (a) that mix of rubber and water is full of air bubbles; however, after 24 hours most of the entrapped air bubbles were released from the mix. This indicates that the repelling water characteristic of rubber particles can be diminished by washing their surface and giving rubber enough time to be submerged in water. In addition, stirring the mix of rubber and water facilitated releasing of the entrapped air bubbles to be detached and release from the mix.

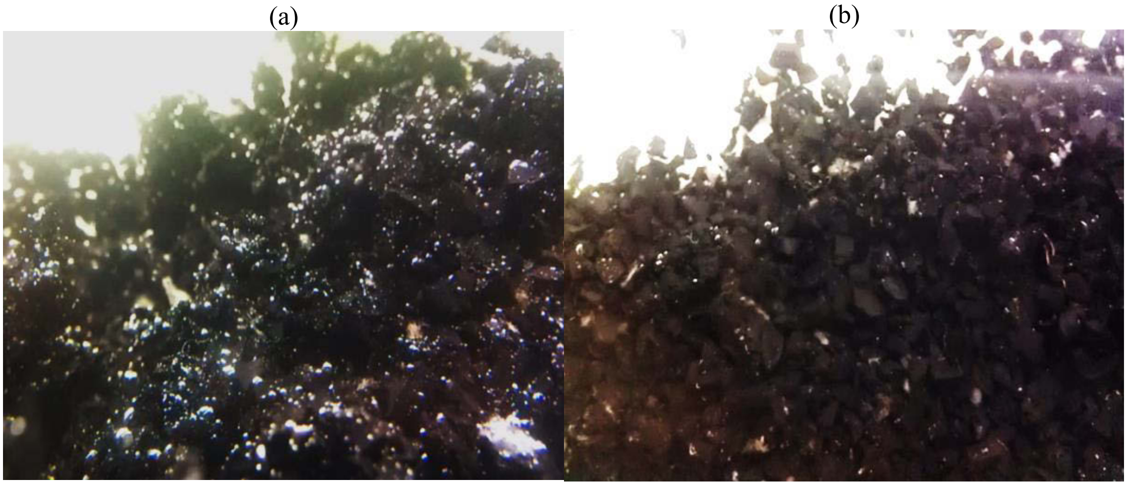


Figure 4.5: Effect of soaking rubber (a) instantly mix of rubber and water is full of air bubbles, (b) after 24 hours most of the air bubbles were released from the mix

Assessment of Water-Soaking Method

The introduced water-soaking treatment method was applied on all the concrete samples, containing rubber in this study. According to the fresh and hardened results, it has been found that the application of this method has positive effects. Moreover, it is easy for application and inexpensive. Both of fresh and hardened properties for samples prepared using water-soaking method were compared to rubberised concrete prepared with untreated rubber. This evaluation sheds light on improving effects of applying the suggested method has on generic mechanical properties of rubberised concrete.

Table 4.3: Mix series prepared for assessment efficiency of the “water-soaking” method

No	Mix ID	Rubber content [%]	Rubber Treatment
1	M/0.40/00CR	00	-
2	M/0.45/00CR	00	-
3	M/0.45/30CR/ARR[2]	30	Untreated rubber
4	M/0.40/20CR/ARR	20	Untreated rubber
5	M/0.40/30CR/24 hr soaked[1]	30	24 hr water-soaked
6	M/0.45/20CR/24 hr soaked	20	24 hr water -soaked

[1]Water-soaked treated rubber, [2]As received rubber without any treatment

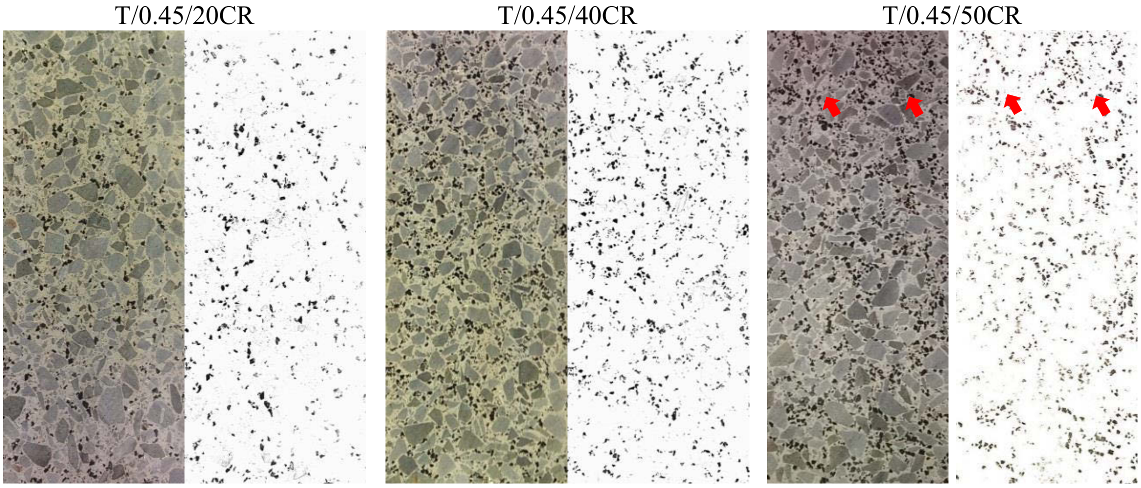
Six series of concrete mixes were investigated to assess the effectiveness of applying water-soaking for different WC ratios and rubber contents (Table 4.3). Results indicated improvement in fresh properties of rubberised concrete prepared with water-soaking method compared to rubberised concrete prepared with untreated (as received) rubber. Results showed similar slump values for both treated and untreated rubber. However, test results for fresh properties revealed that application of the proposed method was effective.

The presented results in Table 4.4 denoted that treated rubber had lower air content (AC) and higher mas per volume (MPV) compared to the mixes contained rubber without treatment. The lower AC indicated reduction in undesirable entrapped air bubbles in the mix, which was 1.5% lower by the average for samples prepared by water-soaking treatment method.

Table 4.4: Fresh properties of mix series using treated and untreated rubber

Mix ID	Vibration duration[s]	WR [L/m³]	Slump [mm]	AC [%]	MPV [kg/m³]
M/0.40/00CR	16-18	3.196	50	1.9%	2442
M/0.45/00CR	16-18	1.151	55	1.5%	2426
M/0.45/20CR/ARR	14-16	1.436	55	4.1	2296
M/0.40/30CR/ARR	14-16	4.351	65	5.9	2245
M/0.45/20CR/24 hr soaked	14-16	1.436	55	3.0	2314
M/0.40/30CR/24 hr soaked	14-16	4.351	65	4.5	2266

A number of studies highlighted some problems regarding homogeneity of the rubberised mix (Jingfu et al. 2008; Youssf & Elgawady 2013). Therefore, it was decided to assess effect of compaction effort on vertical distribution of rubber within concrete matrix. The typical height for a rigid pavement layer is 300 mm in Australia. Accordingly, samples of rubberised concrete with height of 300 mm were prepared. After 7 days, using circular saw, samples were cut vertically to be investigated for vertical distribution of rubber particles. High quality images were taken from the cut faced of 300 mm samples. Then, images were processed and rubber particles were filtered out from the images. It was observed that rubber concentration at top layer of samples prepared with 50% rubber or more was higher than samples prepared with 40% or lower rubber content (Figure 4.6). It was concluded that limiting rubber content to 40% can effectively guaranty uniform distribution of rubber throughout concrete matrix.



T/0.45/20CR T/0.45/40CR T/0.45/50CR

Figure 4.6: Rubber distribution through 300 mm height cut samples; Real images (left), Processed images (right) arrows show high concentration of rubber particles at top layer of sample prepared with 50% of rubber

It should be taken into account that excessive vibration even for mixes that contain low content of rubber results in segregation of rubber and should be avoided. It was observed that concrete contained 40% CR needed a high level of consideration regarding the efforts to be applied to the mix to prevent segregation of rubber.

The optimum level of compaction is a critical issue in rubberised concrete, as a low level of compaction may cause undesirable and poor hardened mechanical properties. On the other hand, a high level of compaction is also undesirable for CRC because it leads to segregation and accumulation of rubber in a layer on the top of concrete mixt, which leads to poor mechanical properties. In this study, a vibrating table was used to apply external vibration for compacting of samples in the fresh state. The applied vibration time was controlled as an indicator of the external effort applied to the concrete samples. In addition, to achieve consistency in compaction, vibration time for samples with same content of rubber was kept constant.

Literature indicates that various methods of rubber treatments are available, which can lead to different hardened results. Table 4.5 presents a brief review of different rubber treatment methods. Washing and drying of rubber particles, introducing organic modifier such as Acetone, Glycerine, CS_2, CCl_4, or inorganic modifier like, $MgSO_4$, $Al_2(SO_4)_3$, $CaCl_2$, and also treatment with NaOH alkaline modifier or acidic modifier such as Acetic acid or Hydrochloric acid were addressed as treatment methods of rubber (Tian et al. 2011).

Table 4.5: Improvement in the compressive strength using various rubber treatment methods (Zheng et al. 2008)

Improvement method		28-day strength [MPa]	Improvement[%]
No modification on rubberised concrete		37.1	Control
Washed with Water and dried		37.2	00.3%
Organic modifier	Acetone	32.4	-12.7%
	Glycerine	33.7	-09.2%
	CS_2	35.9	-03.2%
	CCl_4	36.3	-02.2%
Inorganic modifier	MgSO4	39.5	06.5%
	$Al_2(SO4)_3$	39.1	05.4%
	$CaCl_2$	42.3	14.0%
Alkaline modifier	Ammonia	35.6	-04.0%
	NaOH	35.7	-03.8%
Acidic modifier	Acetic acid	34.2	-07.8%
	Hydrochloric acid	37.6	01.3%

In order to assess the effectiveness of the introduced wet addition of rubber into the concrete mix, the hardened properties of CRC were evaluated at different ages, and the results are presented in Table 4.5. In order to assess the effectiveness of the introduced wet addition of rubber into the concrete mix, the hardened properties of CRC were evaluated at different ages, and the results are presented in Table 4.6.

Table 4.6: Compressive and flexural strength test results using treatment methods

Mix ID	7 days results			28 days results			56 days results		
	Strength [MPa]	SD[1] [MPa]	COV[2] [%]	Strength [MPa]	SD [MPa]	COV [%]	Strength [MPa]	SD [MPa]	COV [%]
Compressive strength f_{cm}									
M/0.45/00CR	45.3	3.2	7.1%	55.6	2.0	3.6%	63.1	3.0	4.8%
M/0.40/00CR	50.5	3.6	7.1%	63.0	3.3	5.2%	71.6	2.4	3.4%
M/0.45/20CR	27.6	1.5	5.4%	34.9	1.3	3.7%	37.5	0.4	1.1%
M/0.40/30CR	27.8	1.2	4.3%	30.9	1.3	4.2%	32.4	0.9	2.8%
M/0.45/20CR/ARR	22.7	1.8	7.9%	27.0	0.9	3.3%	29.6	0.8	2.7%
M/0.40/30CR/ARR	22.1	1.1	5.0%	27.4	0.3	1.1%	27.5	0.3	1.1%
Flexural strength f_{ctm}									
M/0.45/00CR	5.4	0.20	3.7%	6.0	0.25	4.2%	6.0	0.04	0.7%
M/0.40/00CR	6.1	0.14	2.3%	6.9	0.23	3.3%	7.2	0.29	4.0%
M/0.45/20CR	4.2	0.13	3.1%	5.0	0.22	4.4%	5.3	0.33	6.2%
M/0.40/30CR	4.3	0.16	3.7%	5.2	0.14	2.7%	5.6	0.14	2.5%
M/0.45/20CR/ARR	3.8	0.16	4.2%	4.6	0.31	6.7%	5.0	0.23	4.6%
M/0.40/30CR/ARR	4.0	0.09	2.3%	4.7	0.26	5.5%	5.3	0.17	3.2%

[1]standard deviation, [2] coefficient of variance

The results of generic mechanical test for concrete prepared with treated rubber, presented less reduction in samples strength. In addition, it was observed that the improvement was more significant on the compressive strength rather than the flexural strength. Samples containing treated rubber prepared by water-soaking method had 22% and 8% higher compressive and flexural strength, respectively compared with untreated rubber (Table 4.7).

Table 4.7: Strength improvement of samples prepared with water-soaked treated rubber compared to untreated rubber

Rubber content	f_{cm} [MPa]				f_{ctm} [MPa]			
	7-day	28-day	56-day	Average	7-day	28-day	56-day	Average
20% rubber content	22%	29%	27%	22%	11%	9%	6%	8%
30% rubber content	26%	13%	18%		8%	11%	6%	

Evaluation of broken samples showed a stronger matrix of concrete in rubberised concrete with treated rubber, which can be the result of a lower entrapped air content, formation of better bonds between rubber particles and the cement paste as illustrated in Figure 4.7.

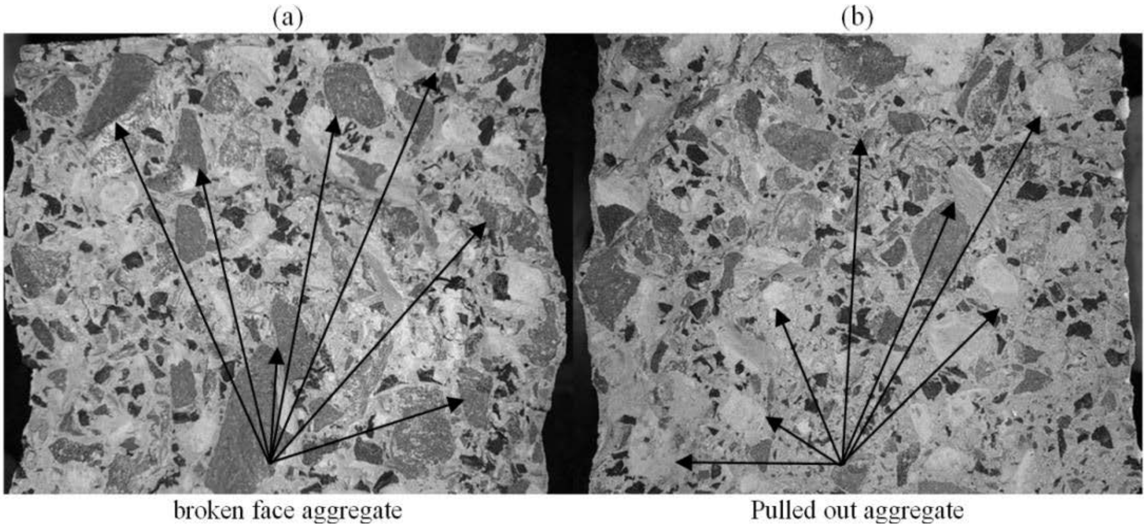


Figure 4.7: Face of samples containing 30% of rubber after flexural test, (a) using water soaked rubber, (b) using untreated rubber

Broken samples of concrete made with the water-soaked method were visually inspected. It was observed that pulled out aggregates and rubber particles have been significantly lower compared to the rubberised concrete with untreated rubber. Thus, it is concluded that the applied method has been very effective in order to increase the bond between rubber and the cement paste.

4.3.2 Treatment of Crumb Rubber with Sodium Hydroxide

Methods of enhancing the bond between the rubber particles and cement paste can be classified into three main categories. The first category involves introducing additives to the concrete mix, such as organic or inorganic salts (Tian et al. 2011), adding special cementitious materials such as silica fume (Youssf & Elgawady 2013) or magnesium cement (Biel et al. Naik 2004), or using Styrene Butadiene Rubber (SBR) latex (Oiknomou et al. 2006), applying cement coatings to the rubber particles or using solutions of cellulose ethers (Li et al. 1998) to improve the mechanical properties of rubberised concrete. The second category involves, physical treatment of rubber particles, such as washing rubber particles with water (Li et al. 2010; Tian et al. 2011) or using rubbers produced in an ambient plant procedure, which results in rubber with rougher surface (Rangaraju et al. 2012). The third category of rubber modification involves chemically treating rubber particles before adding them into the mix. The chemical treatment methods have two main objectives. They are applied to clean the rubber surface of oil, dirt and dust, and they make the surface of rubber rougher (Balaha et al. 2007). Different types of acidic or alkaline solutions have been suggested for this purpose (Tian et al. 2011). According to literature, applying the alkali sodium hydroxide (NaOH) treatment is the method most commonly applied for enhancing the bond between rubber and cement paste (Youssf & Elgawady 2013; Siddique & Naik 2004). However, the provided level of improvement in different studies was not similar (Li et al. 2004; Segre & Joekes 2000; Turatsinze et al. 2007; Turatsinze et al. 2006).

Rubber particles composed of organic components such as isoprene Gualtieri et al. (2005), styrene butadiene (Wik 2008; Khorrami et al. 2010), and also silica compounds are added as reinforcing agents (Wik 2008). Isoprene is an industrial chemical widely used as the basic monomeric unit in natural rubber (Gualtieri et al. 2005). In addition, styrene butadiene rubber (SBR) is the most commonly used rubber polymer in passenger car tyres (Wik 2008). Accordingly, when sodium hydroxide comes into contact with the surface of crumb rubber, it reacts with isoprene, styrene butadiene and other organic components of the tyre (Khorrami et al. 2010). Moreover, silica in rubber aggregate can react with strong alkali solution to form an alkali-silica reaction (ASR). These reactions make the surface of the crumb rubber rougher (Balaha et al. 2007), which may result in better bond characteristics between the rubber and paste. In contrast, it has been reported that treatment with sodium hydroxide can create pores on the surfaces of rubber particles, where air bubbles may be entrapped during concrete mixing. These air bubbles may remain in the concrete matrix, and reduce concrete strength (Khorrami et al. 2010).

Treatment of rubber with NaOH solution has been used to improve mechanical characteristic of rubberised concrete. Besides, the application of this method is relatively lower in price than other chemical modifying methods. In order to assess the effectiveness of applying this treatment method, the most important property of concrete, which is its compressive strength, should be evaluated. Besides, the compressive strength can also represent as a good indicator of many of the other mechanical properties of concrete such as modulus of rupture, indirect tensile strength and modulus of elasticity.

The results of applying NaOH treatment in literature were scattered. Therefore, the application of this method is aimed to be optimised in this study. Some investigations showed that the application of this method was effective and the concrete strength improved moderately or even dramatically (Balaha et al. 2007; Pelisser et al. 2011; Youssf & Elgawady 2013; Siddique & Naik 2004; Pacheco-Torgal et al. 2012). In contrast, negative impact of this method on the strength of rubberised concrete was reported by some investigations (Tian et al.2011; Khorrami et al. 2010). Moreover, other studies revealed that the application of NaOH had a marginal effect, and the strength of concrete prepared with NaOH treated rubber were the same as untreated ones (Li et al. 2004; Segre & Joekes 2000; Turatsinze et al. 2007).

The variety of outcomes resulted from NaOH treatment shows the importance of studying this treatment mechanism in more depth. The sodium hydroxide solution is a heavy duty cleaner and can clean rubber particles from dust, oil and dirt (Khorrami et al. 2010). The mentioned oil and dirt on the surface of rubber particles can make an unwanted layer between cement paste and rubber surface, which can be a source of defect in the formation of strong adhesion between rubber-surface and cement paste. In addition, zinc stearate is an additive, which is added to tyre rubbers to make them more resistant to oxidation. Existence of zinc stearate on the surface of rubber leads to poor adhesion characteristics. Zinc stearate creates a barrier layer on the rubber surface, which makes the rubber particles hydrophobic; thus the surface of rubber tends to trap to air bubbles, which are adhered to rubber (Youssf & Elgawady 2013; Pelisser et al.

2011). Furthermore, It was reported that a large number of air bubbles entrapped by untreated rubber, when it was added to the water (Khaloo et al. 2008). This comes from the water repelling behaviour of rubber particles resulted from the effect of zinc compound on its surface. During NaOH treatment, zinc stearate turns to sodium stearate, which is soluble in water. As a consequence, it can be removed from the rubber surface if rubber is rinsed properly after the treatment (Segre et al. 2002).

Literature reported that treatment of rubber with sodium hydroxide can provide a rougher surface for rubber particles (Balaha et al. 2007). This improvement increases the contact surface between rubber and the cement paste and makes the bond between them stronger. Treating rubber with NaOH solution results in rubber with rougher surface, on the other hand, the produced rough surface can trap air inside if it is deep enough to act similarly to pores of lightweight aggregate. A very low increase in the air content (e.g. 2%) results in severe decrease of the compressive strength (e.g. 10%) (Neville & Brooks 2010; Austroad 2009). Therefore, the roughness level of rubber particles should be balanced and optimised.

The alkali solution cannot have significant effect on rubber particles if the time of treating with NaOH solution is not selected long enough, or the alkali solution is not strong enough. In contrast, putting rubber particles for a long period of time in the alkali solution can damage rubber particles and make their surfaces rougher. This study investigates a procedure to optimise NaOH rubber treatment. The effect of the proposed method is assessed based on improvement achieved on generic mechanical behaviour of crumb rubber concrete (CRC). Using the introduced method may mitigate the negative effects of rubber incorporation into the concrete mix, and enable concrete producers to increase rubber content of rubberised concrete pavement.

Introduction of Sodium Hydroxide Treatment

Literature denoted different durations for keeping rubber particles in the sodium hydroxide solution in order to conduct the treatment. Some studies performed the rubber treatment only for a short duration of time 5 to 30 minutes (Segre & Joekes 2000; Khorrami et al. 2010; Balaha et al. 2007; Siddique & Naik 2004; Segre et al. 2004), while others accomplished treatment in a longer duration of 24 hours (Tian et al. 2011). In order to optimise the timing of rubber treatment in solution different ages for treatment were selected. This study investigated treatment timing for periods of 20 minus, 2 hours, 24 hours, 48 hours and 7 days.

In order to perform treatment of rubber particles, a large saturated solution of sodium hydroxide was prepared. This was carried out using identical solution concentration and consistent modification of rubber. To keep the consistency, NaOH solution in volume of 150 litres with pH of 14 and concentration of 10% was prepared. Then, rubber particles were put in different containers containing the prepared saturated NaOH solution. The volume of modifier solution in each container was set to be 10 times larger than the volume of rubber. Thereafter, five containers with 30 litres of saturated NaOH were prepared, and 3 litres (3.45 kg) of crumb rubber were put in each container. Then, mixes of rubber and the solution stirred regularly to guaranty a uniform treatment of rubber particles. Figure 4.8 presents some samples, taken from containers at the end of different treatment durations. It was observed that colour of sodium hydroxide solution changed continuously from light yellow to the dark yellow by the increase of the treatment period. It can be seen that the continuous change of the colour of solution revealed the chemical reaction of sodium hydroxide solution with rubber. The reaction was not limited only to the physical washing of rubber surface from dust and dirt and continued over the period of 7 days.

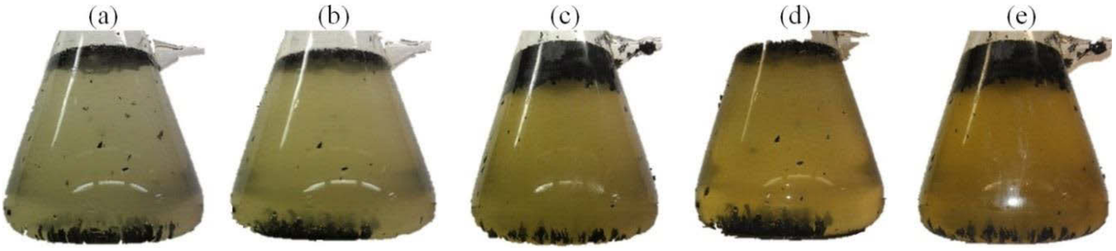


Figure 4.8: Samples at different treatment duration (a) after 20 minutes, (b) after 2 hours, (c) after 24 hours, (d) after 48 hours, (e) after 7 days

Afterwards, the rubber particles were rinsed to be cleaned from alkali solution. Rinsing with water was continued until the measured pH of washed rubber particles placed in the range of pH of 7±0.1. The next step of this study was included taking SEM photos from the surface of treated rubber particles. The aim of this part of the investigation was to classify rubber particles based on treatment time and surface roughness.

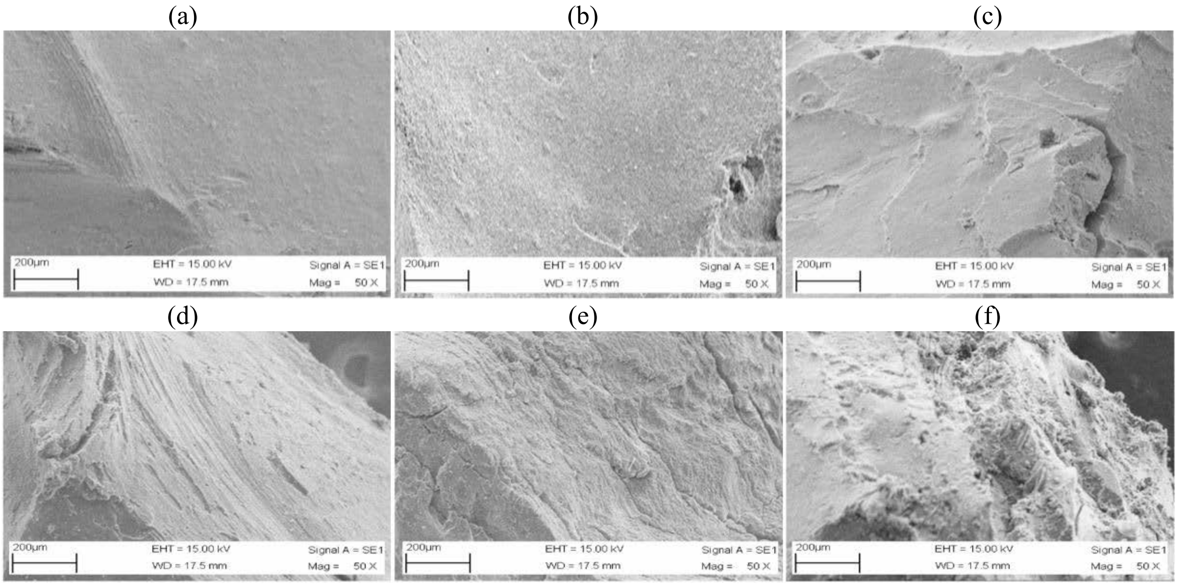


Figure 4.9 SEM micrographs of crumb rubber surface taken in the scale of 200µm (a) no treatment, (b) after 20 minutes, (c) after 2 hours, (d) after 24 hours, (e) after 48 hours, (f) after 7 days

Photos in scale of 200 µm were taken using SEM. Images in Figure 4.9 indicates that the reaction of NaOH with rubber particles made the surface of rubber particles rougher. It was observed that the surface of 20 minutes and 2 hours modified rubbers had almost the same roughness. On the other hand, surfaces of 24 and 48 hours modified rubber were classified in the same group. Finally, the surface of treated rubber in the period of 7 days was found to be much rougher than the surface of the other series of treated rubber, and it was categorised in a separate group.

The outcome of this step was the selection of three groups of rubber to be used for making crumb rubber concrete. Lightly treated, moderately treated and heavily treated rubbers incorporated into concrete samples and test results of rubberised concretes were compared to each other in order to select the optimised treatment duration.

Assessment and Optimisation of NaOH treatment Method

In order to optimise the NaOH treatment duration, two series of mixes were made and assessed for both fresh and hardened properties. The only difference between samples of each mix series was the treatment duration, (i.e. 20 minutes, 24 hours and 7 days). In terms of fresh properties, the slump number, air content (AC) and mass per unit volume (MPV) were assessed. Moreover, the compressive strength, the flexural strength and the modulus of elasticity tests were performed to investigate the optimised duration of crumb rubber treatment.

It is stated by different studies that the crumb rubber inclusion into the concrete mix results in reduction of workability and lower slump number (Rangaraju et al. 2012; John & Kardos 2011; Khaloo et al. 2008; Siddique & Naik 2004; Khatib & Bayomy 1999; Taha et al. 2009). The decrease of workability is found to be consistent with the increase of rubber content as rubber particles enhance the mix viscosity (Sgobba et al. 2010). Majority of studies indicated the reduction in the slump number by adding rubber into the concrete mix; however, there is not a consensus on the extent of slump reduction.

Previous studies have focused on the slump of mix series with a variety of rubber content. However, this study aims to investigate the effect of rubber treatment on fresh properties of rubber. Therefore, slump is not defined as a variable under the scope of this study. It was aimed to prepare rubberised mix series with slump of 60 mm according to the Australian road specifications. Although, introducing rubber into the mix reduces workability, the effect of rubber inclusion should compensate by adjusting WR admixture content. The slump test was performed in accordance with the Standard AS1012.3.1, and the results are demonstrated in Figure 4.10 (a).

Introducing same content of crumb rubber and WR into the mix series, similar slump numbers were achieved for different types of treated rubber. Hence, it can be concluded that different duration of rubber treatment does not have a significant effect on workability of the mix. The slump results were on the contrary with the general effect of coarser fine aggregates, have on slump reduction. The internal friction and workability of the mix is affected by roughness, and also the coarseness of aggregates. While roughness is considered as a function of surface texture of concrete aggregates, coarseness is a function of aggregate shape. Modification of rubber only had an effect on surface roughness and did not change the shape of rubber particles; thus, the coarseness of the modified rubber was almost the same. The low content of rubber in the mix, which is 20-30% of volume of fine aggregate (roughly less than 10-15% of the total volume of concrete aggregates), can be justified as the main reason for insignificant effect that treating rubber has on slump. Test results of compacting factor were considered complementary set of data, which demonstrated workability of rubberised mixes. Results noted that by adjusting slump to 60±10 mm, the compacting factor remained the same value of 89±2 mm for all mixes, as demonstrated in Figure 4.10 (b).

Air content (AC) was another characteristic of the mix series, which was assessed. AC is an important factor due to the negative impacts it has on the compressive and flexural strength, and also durability of concrete pavements. Many studies have reported higher ACs for rubberised concrete (Khaloo et al. 2008; Siddique & Naik 2004; Youssf & Elgawady 2013; Rangaraju et al. 2012; John & Kardos 2011; Taha et al. 2009; Li et al. 2004). Generally concrete with higher air content has lower strength. In addition, concrete with higher than 6% AC is not desirable for rigid pavements (Austroad 2009; RTA R83 2010).

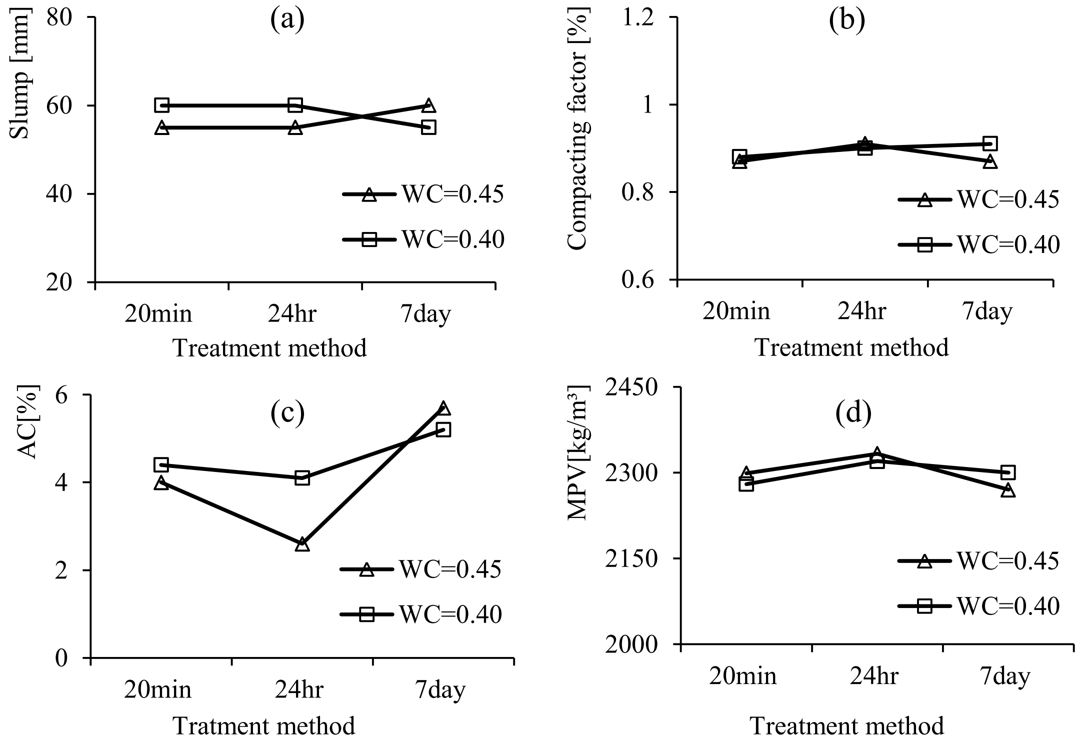


Figure 4.10 Determining the optimum time of treating rubber based on concrete fresh properties (a) slump, (b) compacting factor, (c) air content and (d) mass per unit volume

Results presented in Figure 4.10 (c) revealed that different durations of treating rubber with NaOH had different outcomes. Results indicated that the optimum point of the AC was achieved for the 24-hour duration of treating rubber, where the AC of rubberised concrete had the minimum value. It is well-known that the density of concrete is reduced by adding recycled tyre rubber (Siddique & Naik 2004; Khaloo et al. 2008). This is expected as the density of rubber is lower than other solid concrete constituents (Fattuhi & Clark 1996; Sgobba et al. 2010). Moreover, rubber particles entrap air into the mix, which increases the mix AC and results in lowering the MPV (Rangaraju et al. 2012; Youssf & Elgawady 2013; John & Kardos 2011).

As it can be seen from Figure 4.10 (d), test results of this research revealed that different durations of rubber treating with NaOH resulted in different MPVs. Although, content of rubber was set similar for each array of samples, MPV results revealed that the samples prepared with 24-hour treated rubber had the highest MPV value. According to literature, concrete with higher density, has higher strength (Neville & Brooks 2010; Mehta et al. 2006). This means that samples with the same mix constituents, the one with higher MPV is expected to have higher strength and durability properties.

The results of fresh property tests showed that treatment of rubber did not have significant influence on slump and the compacting factor. However, the air content and the mass per unit volume were affected by rubber prepared with different treated methods. Considering the fresh property results the method of treating rubber for duration of 24 hours was found the best method, which provided the most promising results.

Mechanical properties of concrete are dependent on both constituent materials and the procedures applied for batching preparation and mixing of concrete (Neville & Brooks 2010; Mehta et al. 2006). In this investigation, each set of mix series contained the same raw materials and rubber content, but rubber was prepared by different treating methods. Based on literature, the major expectation, regarding introducing of rubber at any size or content into concrete, is the reduction in the compressive strength , the flexural strength, and the modulus of elasticity (Zheng et al. 2008; Topcu 1995; Kaloush et al. 2005; Rangaraju et al. 2012). Each prepared mix series had same content of rubber and aggregate.

However, it can be observed from the results shown in Figure 4.11 (a and b), the application of different treatment durations significantly affected the compressive strength of concrete. All reasons lead to reduction of strength, which relies on rubber content of concrete should be considered same for all samples in each mix series. While the concentration of rubber particles was the same for different mix series, the better compressive strength test result means the better bond formation. The test results for compressive strength showed that the optimisation of treatment duration provided the most promising strength results.

The tensile flexural strength is a highly important characteristic of concrete pavement to avoid serious cracking under traffic loads. The 28-day concrete flexural strength is a key parameter in design of pavement in Australia, which is used in the determination of pavement thickness in Australia. A decrease in the flexural strength is noted by literature as the CR content increased (Youssf & Elgawady 2013; Khorrami et al. 2010; Kaloush et al. 2005; Ganjian et al. 2009; Li et al. 2011), and it is expected since the compressive strength decreases with the increase of rubber content.

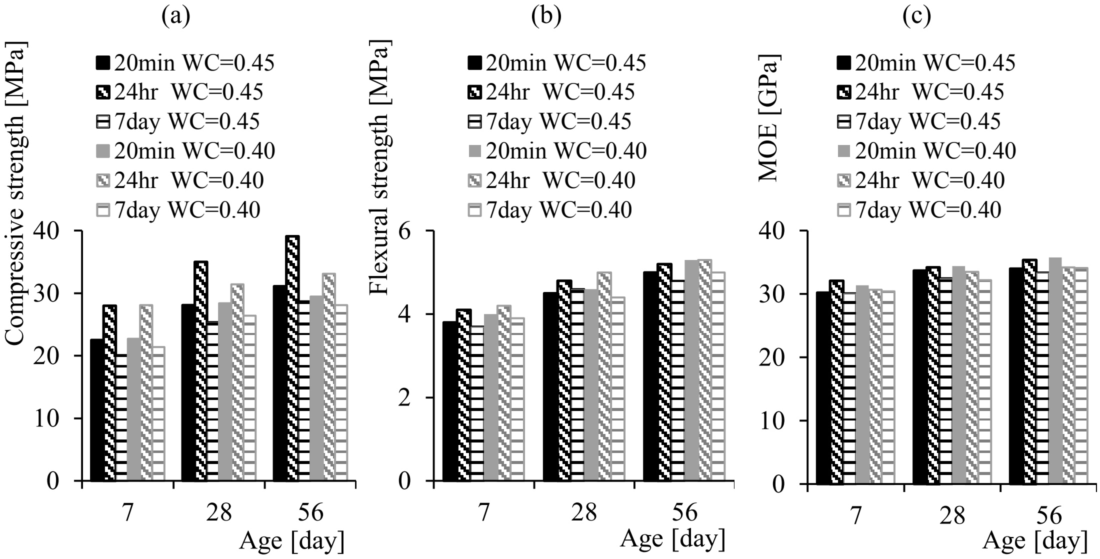


Figure 4.11 Optimising the duration of rubber treating based on the hardened properties

Samples prepared with 24-hour treated rubber showed the highest strength for both of the WC ratios at different ages. The highest compressive strength, achieved for treated rubber with duration of 24 hours compared to the durations of treatment as demonstrated in Figure 4.11 (a and b). The achieved improvement on strength is more promising for compressive results than flexural strength.

The modulus of elasticity is another key property of pavement concrete since it impacts the serviceability and performance of pavement (Zheng et al. 2008). A stiffer pavement will generate more stresses if a unit change in length applies to it. In other words, the possibility of cracking due to the applied external strain is higher for concrete with the higher modulus of elasticity. As a result, if an external strain is applied on different concrete samples in restrained condition, the one with lower elastic modulus will generate lower stresses. The elastic modulus of concrete is closely related to properties of cement paste and stiffness of concrete aggregates (Topcu 1995). Therefore, rubberised concrete has lower elastic modulus than plain concrete (Khaloo et al. 2008; Kaloush et al. 2005). The reduction of MOE due to the use of rubber aggregates can logically be justified by the well-established fact that the MOE of a concrete depends on the modulus of elasticity of the volumetric proportion of concrete constituents (Ho et al. 2009). Consequently, the reduction in MOE value is considered an advantage, which rubber modification provides for pavement concrete, and results in the lower sensibility to thermal or shrinkage volume changes.

It is denoted by literature that MOE values decreases with an increase in rubber content (John & Kardos 2011; Zheng, Huo & Yuan 2008; Youssf & Elgawady 2013). Test results demonstrated in Figure 4.11 (c) indicated that different durations of treating rubber do not significantly affect the modulus of elasticity. It can be justified by taking into account the underlying concept of AS1012.17 test method. This test limits the stress of samples up to 40% of the maximum stress of concrete. Hence, under the limitation set by Australian standard for the test, the possible improvement in the bond between rubber and cement paste, which can positively influence and prevent acceleration of the crack propagation in concrete, is not actively involved in MOE test.

The ultimate tensile strain capacity of pavement concrete was assessed if any improvement achieved regarding the increase in the strain at the failure. For all flexural samples, LVDT measures were set in mid-span point of the samples, in order to measure the deflation of samples under the load.

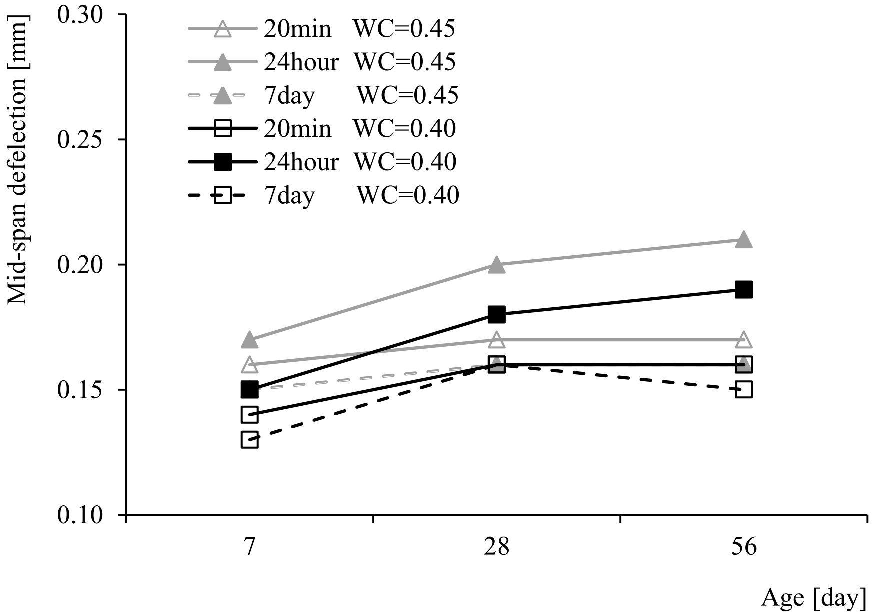


Figure 4.12 Effect of rubber treatment duration on the ultimate tensile strain capacity

Samples with higher deflection are more ductile and can resist higher flexural strain before failure. For different ages, the mid-span deflections at the maximum flexural loads were recorded and compared with the results achieved from other samples. Results demonstrated in Figure 4.12 showed the mid-span deflections of the 24-hour treated rubber provided the better results at different concrete testing ages compared to the other durations of treatments.

Broken samples from the compressive and flexural strength test which are prepared with 24-hour and 20-minute treatment duration are illustrated in Figure 4.13. Concrete samples that were prepared with 24 hours of treatment duration had more shredded rubber particles on their broken surfaces. In contrast, relatively more pulled out rubber particles were observed on the surfaces of concrete, which prepared with rubber treated for duration of 20 minutes. According to the results obtained in the present experimental research, the 24 hours of treatment resulted in the best outcomes in term of both fresh and hardened properties, and it was selected as the optimum duration for rubber treatment.

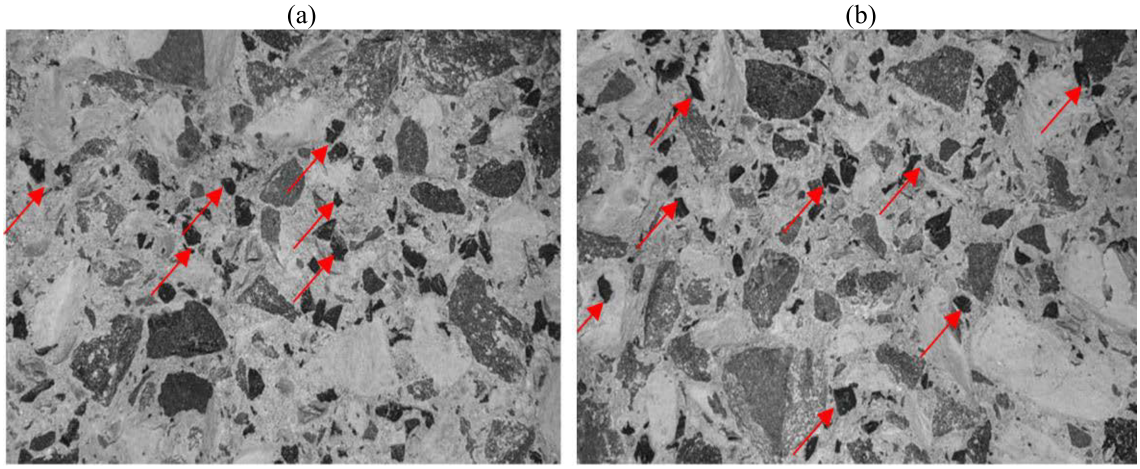


Figure 4.13 Effect of rubber treatment duration at (a) 24-hour treatment duration more shredded crumb rubber observed, (b) at 20-minute treatment duration more pulled out crumb rubber observed

Results achieved for hardened properties of concrete with the same rubber content and different sodium hydroxide treatment durations indicated that changing treatment duration significantly affects compressive strength. In addition, it was found that changing treatment duration has a moderated effect of flexural strength and ultimate deflection of test samples. Moreover, it does not have significant effect on modulus of elasticity. In general, the experimental results for fresh and hardened properties indicated that the sodium hydroxide treatment had the optimum duration of 24 hours.

4.2 Evaluation of Rubberised Concrete contains Optimised Treated Rubber

In the previous stage of this investigation, the optimised duration of treating rubber was determined. In this section, properties of concrete samples prepared with optimised treatment duration of 24 hours, were compared to rubberised concrete prepared with untreated rubber with the same content of rubber.

Series of samples were prepared with water-cement ratios of 0.40 and 0.45, and rubber contents of 30% and 20%, respectively. In addition, some control samples (samples with no rubber) were prepared. The fresh and hardened properties of concrete were investigated for both of the mix arrays, and test results are shown in Table 4.8.

Table 4.8: NaOH treatment fresh and hardened property results for

Fresh properties

Mix ID	WC	WR [L/m³]	Rubber Content [%]	Slump [mm]	AC [%]	MPV [kg/m³]
0.45/00CR	0.45	1.151	0	50	1.9	2442
0.45/20CR/24h	0.45	1.436	20	55	2.6	2333
0.45/20CR/ARR	0.45	1.436	20	55	4.1	2296
0.40/00CR	0.40	3.196	0	55	1.5	2426
0.40/30CR/24h	0.40	4.351	30	65	3.5	2297
0.40/30CR/ARR	0.40	4.351	30	65	5.9	2245

Hardened properties

Mix ID	Compressive strength [MPa]			Flexural strength [MPa]			Modulus of elasticity [MPa]		
	$f_{cm,7}$	$f_{cm,28}$	$f_{cm,56}$	$f_{ctm,7}$	$f_{ctm,28}$	$f_{ctm,56}$	$MOE_{,7}$	$MOE_{,28}$	$MOE_{,56}$
0.45/00CR	45.3±3.2	55.6±2.0	63.1±3.0	5.4±0.2	6.0±0.3	6.0±0.0	39.4	42.3	43.6
0.45/20CR/24h	28.0±1.1	35.0±1.7	39.1±1.0	4.1±0.1	4.8±0.2	5.2±0.0	32.1	34.2	35.4
0.45/20CR/ARR	22.7±1.8	27.0±0.9	29.6±0.8	3.8±0.2	4.6±0.3	5.0±0.2	32.3	34.4	35.3
0.40/00CR	50.5±3.6	63.0±3.3	71.6±2.4	6.1±0.1	6.9±0.2	7.2±0.3	42.4	46.5	48.4
0.40/30CR/24h	28.1±1.2	31.4±1.2	33.1±1.2	4.2±0.2	5.0±0.2	5.3±0.2	30.7	33.5	34.2
0.40/30CR/ARR	22.1±1.1	27.4±0.3	27.5±0.3	4.0±0.1	4.7±0.3	5.3±0.2	30.9	33.6	35.3

Test results for both of mix series with WC of 0.40 and 0.45 showed a higher value of air content compared to samples without rubber inclusion. In addition, the higher increase in the value of AC was observed in untreated rubber samples. According to the results demonstrated in Table 4.8, it can be concluded that introducing rubber to concrete increased the AC and reduced MPV.

However, samples prepared with 24 hours of treating rubber had more promising results compared to the untreated rubber. Furthermore, results indicated that for both of the sample series prepared with treated and untreated rubber, slump numbers for mixes were similar. It means that treatment of rubber does not have a significant effect on workability of the mix. Sand content of concrete plays an important role in concrete strength (Neville & Brooks 2010). Hence, any reduction of sand content replaced with rubber will result in a weaker matrix and lead to a lower compressive strength. The mechanical test results confirmed that compared to the samples prepared without rubber, rubberised samples had 54% and 27% lower compressive and flexural strength, respectively. However, samples prepared with optimised-treated rubber showed less reduction in strength. The strength improvement achieved for treated rubber with duration of 24 hours compared to the untreated rubber and was more promising for compressive results than flexural strength as demonstrated in Table 4.9.

Table 4.9: Improving effect of optimised treating rubber on strength

Ratio of (24hour treated/untreated) rubber	Compressive strength [MPa]			Flexural strength [MPa]		
	$f_{cm,7}$	$f_{cm,28}$	$f_{cm,56}$	$f_{ctm,7}$	$f_{ctm,28}$	$f_{ctm,56}$
0.45/20CR	23%	30%	32%	9%	4%	4%
0.40/30CR	27%	15%	20%	5%	7%	1%
Average improvement	25%			5%		
Standard deviation of improvement	±6%			±3%		

It can be seen from Table 4.9 that compressive strength was 25% higher for samples prepared with optimised duration of NaOH treatment. The standard deviation of the achieved results was 6%. On the other hand, using the proposed 24-hour duration treatment method, the achieved improvement in flexural strength was only 5%. Considering the standard deviation of results the improvement achieved for flexural strength is justified insignificant. Taking into account results of the compressive and flexural strength tests over time it can be denoted that the pattern of strength gaining is affected by adding rubber. Samples with rubber inclusion developed less strength in long-term. However, the magnitude of the strength reduction was lower for samples prepared with 24-hour treated rubber.

Broken samples from the compressive tests showed a transition in failure mode from a conical-shear failure mode to a tensile failure cracking mode, when rubber was introduced to the mix series (Figure 4.14). As a consequence, by introducing rubber to concrete large numbers of visible tensile cracks were appeared on the surface of the broken samples. These cracks, which are demonstrated in Figure 4.14 (c and d), were parallel to each other. Moreover, it was observed from Figure 4.14 (b) that the treatment of rubber in the optimised duration made a better bond between the cement paste and rubber, which leaded to less tensile-splitting cracks. Finally, the modulus of elasticity reduced 23% by adding crumb rubber. This reduction was found to be similar for both types of concrete series with treated or untreated crumb rubber.

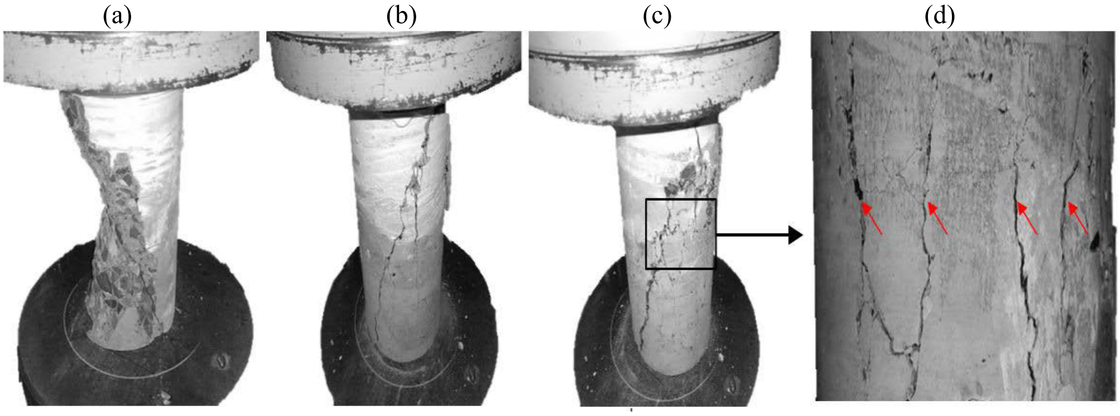


Figure 4.14 (a) No rubber: conical-shear failure mode; (b) 30% 24-hour NaOH treated rubber: shear failure mode with limited tensile cracks (c) 30% untreated rubber: less shear failure mode and more splitting-tensile failure mode, formation large number of parallel cracks in tensile failure mode

In general, results revealed that the concrete strength was reduced for both types rubberised concrete, with or without treatment. However, using the optimised sodium hydroxide treatment method, the prepared rubberised concrete had a relatively less strength reduction. It was observed that the improvement was more significant for compressive strength rather than flexural strength. Compared to untreated rubber, samples prepared by optimised sodium hydroxide treatment rubber had 25% and 5% higher compressive and flexural strengths, respectively. SEM images of rubber particles indicated that when sodium hydroxide treatment was extended from 20 minutes to 7 days, the surfaces of the rubber particles became rougher. However, Fresh and hardened test results of the rubberised concrete revealed that the rougher surface of the crumb rubber particles did not lead to better adhesion characteristics of the rubberised concrete for all treatment methods used. According to results achieved from the inspection of SEM images, three periods of treatments involved 20 minutes, 24 hours and 7 days were examined. Experimental results revealed that the sodium hydroxide treatment had the optimum duration of 24 hours. Applying treatment for 20 minutes duration was found not to be sufficient. Similarly, longer treatment duration of 1 week also proved the deficiency of the treatment.

It can be summarised that the required treatment duration may vary based on the extent of rubber surface dirtiness, source tyres constituents' properties and concentration of the alkali solution. It is highly recommended for any attempt regarding the use of NaOH treated crumb rubber in concrete, trial mix series be prepared with the three suggested periods of 20 minutes, 24 hours and 7 days. Thereafter, the decision regarding the optimum duration of treating rubber with sodium hydroxide can be made based on the result of trialled periods.

4.3.3 Selection of Rubber Treatment Method

An experimental study was carried out to assess crumb rubber concrete properties in which the crumb rubber particles were treated based on two different methods. Accordingly, application of the "Water-Soaking" method and Sodium Hydroxide (NaOH) treatment were evaluated. Referring to the results, the following concluding remarks can be drawn:

The innovate method of water-soaking presented and evaluated because of its advantages including:

(a) It is an inexpensive and practical procedure;

(b) It can make homogenous and evenly distributed rubber particles in the concrete mix with a lower entrapped air,

(c) It improves the formation of the bond between rubber particles and cement paste.

The test results of rubberised concrete contained water-soaked rubber were compared to the test results of a rubberised concrete type with untreated rubber. It can be noted that the treated rubberised concrete had a relatively less strength reduction. It was observed that the improvement was more significant for compressive strength rather than flexural strength. Compared to untreated rubber, samples contained water-soaked rubber had 22% and 8% higher compressive and flexural strengths, respectively,.

On the other hand, the alkali treatment by solution of Sodium Hydroxide (NaOH) was applied in order to maximise the crumb rubber concrete strength. It was observed that the crumb rubber treated for the period of 24 hours had the best results. As a consequence, it is concluded that treating crumb rubber had optimum duration of 24 hours with sodium hydroxide solution, and applying treatment in a shorter or longer period can reduce the efficiency of treating rubber with sodium hydroxide solution.

However, the required treatment duration may vary based on the level of rubber surface dirtiness, properties of constituents of source tyres and concentration of the alkali solution. It is highly recommended for any attempt regarding the use of treated crumb rubber, trial mix series prepared with the three suggested periods of 20 minutes, 24 hours and 7 days. Afterwards, the decision regarding the optimum duration of treating rubber with sodium hydroxide can be made. Results revealed that the concrete strength was reduced for both rubberised concrete with or without treatment; however, the reduction was much less for the treated rubber. Concrete prepared with the optimised-NaOH treated rubber had 25% higher compressive strength compared to the concrete with the same content of untreated rubber.

This research drew a comparison between applications of different treatment methods. Although the application of Sodium Hydroxide (NaOH) treatment resulted in marginally higher strength for rubberised concrete, the relative difficulty and higher cost associated with the application of this method led to the used of "water-soaking" treatment method. This method was found inexpensive and practical procedure. Moreover, using this method brought with promising results regarding the even distribution of rubber particles in the concrete mix, lower entrapped air, and the formation of the better bond between rubber particles and the cement paste. As a consequence, it was decided to select "water-soaking" treatment method for treating rubber, which was introduced into all main mix series.

4.4 Properties of Main Mix Series

The mixing procedure applied in this study was the same as procedure specified by the Standard AS 1012.2. Adjustment of slump to target slump was accomplished using WR Plastiment10, which was added within the first minute of mixing cement and water. The mixing procedure started with 1 minute of pre-mixing of dry aggregates and rubber, and then continued for 2 minutes to further mix the concrete. After that a rest period of 2 minutes was applied. Then, an additional 2 minutes of mixing was applied. Initial slump was measured within the next 3 minutes. Again, 2 minutes of mixing was applied before measuring the slump for a second time. Slump was required to be measured within a 3 minute period. The total duration of mixing was confined to not be more than 14 minutes in accordance with the Standard AS 1012.2. Australian Standard AS 1012.2 was followed for the rest of the procedure. However, the standard mixing sequences modified slightly to achieve a more uniform mix and more homogenous distribution of rubber particles in the prepared mix with less entrapped air. A mix of rubber and water, adjusted based on the target WC ratio, was added to the mix.

Table 4.10: The results of fresh properties for the main mix series

Mix ID	WC	CR [%]	Vibration duration[s]	WR [L/m^3]	Slump [mm]	AC [%]	MPV [kg/m^3]	CF [%]
M/0.40/00CR	0.40	00	16-18	3.196	50	1.9%	2442	0.85
M/0.40/10CR	0.40	10	16-18	3.990	60	2.4%	2387	0.88
M/0.40/20CR	0.40	20	14-16	3.945	60	3.2%	2319	0.89
M/0.40/30CR	0.40	30	14-16	4.351	65	4.5%	2266	0.89
M/0.40/40CR	0.40	40	12-14	4.443	65	6.1%	2213	0.89
M/0.45/00CR	0.45	00	16-18	1.151	55	1.5%	2426	0.87
M/0.45/10CR	0.45	10	16-18	1.225	65	2.1%	2370	0.88
M/0.45/20CR	0.45	20	14-16	1.436	55	3.0%	2314	0.90
M/0.45/30CR	0.45	30	12-14	1.554	55	4.3%	2253	0.90
M/0.45/40CR	0.45	40	10-12	2.072	65	5.6%	2142	0.92

Treated rubber prepared by using water soaking method was introduced into all mix series. In this step, the trial results of the proportioning mix series from the previous step were further refined for optimisation of rubber in the mix series and are shown in Table 3.9. According to the results of trial mix series, rubber content was limited to up to 40% and WC ratio for rubberised concrete was selected 0.40 and 0.45. In addition, test results of fresh properties are listed in Table 4.10.

4.4.1 Test Results and Discussion on Fresh Properties

Slump and Compacting Factor

Slump has not been a variable for this study. It was aimed to have slump number of 60±10 mm for all mix series. It was observed that the required water-reducer (WR) to set the slump on target value of 60±10 mm increased based on the increase in rubber contents. As a consequence, it can be observed from Table 4.10 that to achieve the same slump of 60±10 mm, content of WR was required to be increased roughly three folds for the mix series prepared with WC=0.40 compared to the mix series with WC=0.45.

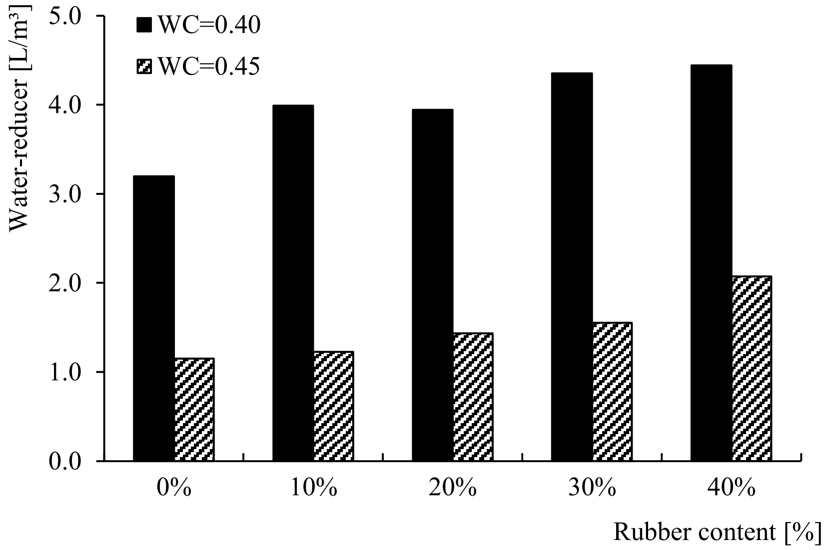


Figure 4.15: The required water-reducer for achieving 60±10 mm slump number

By adding the required WR to each mix series, the measured slump number was the same in the range of 60±10mm, for all mix series (Figure 4.15). The complementary data from the compacting factor (CF) test revealed the same CF values in the range of 0.85-0.92 for all the prepared mix series (Table 4.10).

Air Content

Results of this study showed that the addition of more rubber increased the AC values in a parabolic pattern as shown in Figure 4.16. In addition, mix series with lower WC had higher AC. Generally a concrete with a higher air content has lower strength (Neville & Brooks 2010). However, having the minimum AC of 3% is preferable due to its effect on durability and freeze-thaw resistance. It was observed that by introducing 20% rubber or more the AC of concrete samples increased to a level greater than 3%.

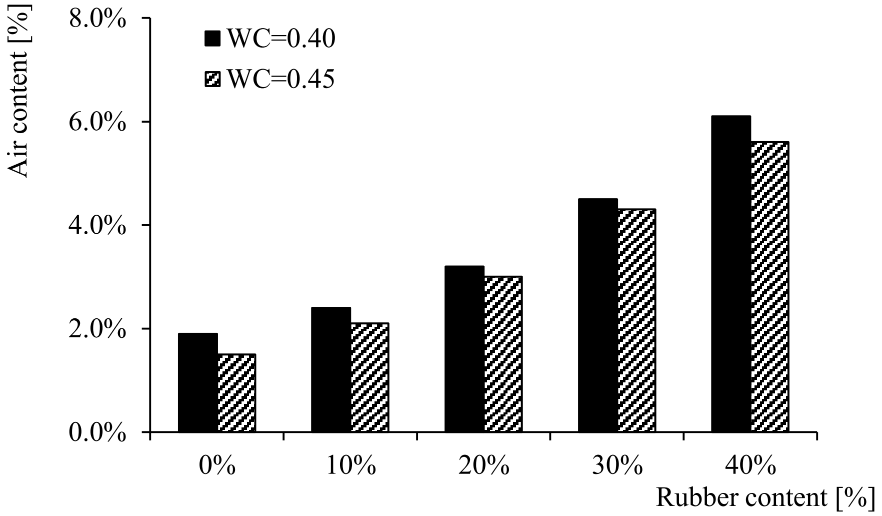


Figure 4.16: AC of mix series increased by the increase of rubber content

Bleeding

The effects of rubber on bleeding properties of concrete were also evaluated in this research. The results presented in Figure 4.17 (a) show a reduction of bleed water by the increase of rubber content for both of the mix arrays with WC ratios of 0.40 and 0.45. Considering only the volume of bleed water is not a proper way to compare mix arrays with different WC ratios and water contents, because those properties substantially affects the bleeding properties of concrete. The Australian Standard AS1012.6 provides a relationship for quantifying bleeding in a standard and consistent way.

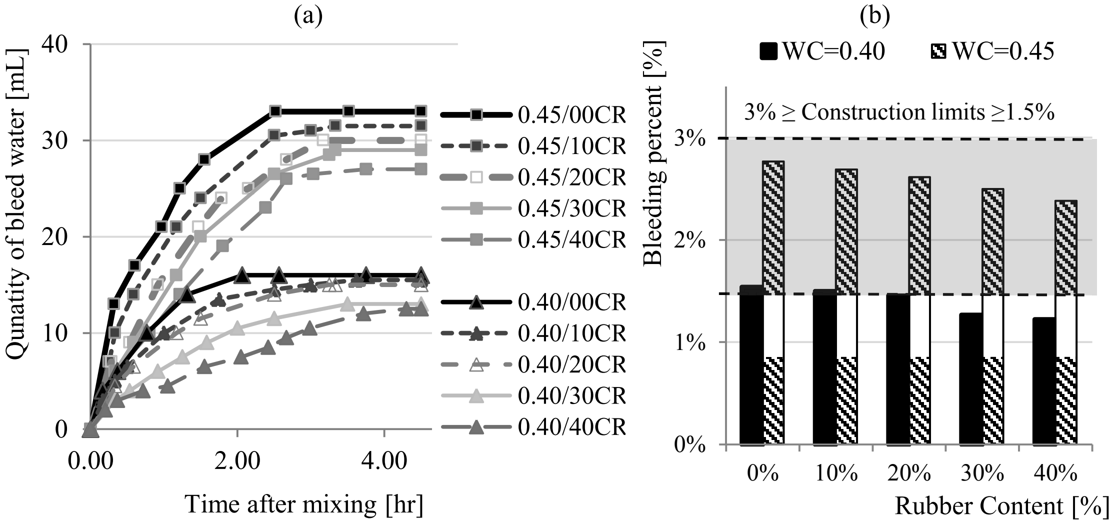


Figure 4.17: (a) Quantity of bleed water and (b) calculated bleeding percent index vs. concrete pavement mix limits

In Australia 1.5% to 3% bleeding water is expected for concrete pavement. On the one hand, a low bleeding rate results in a low paste volume on the surface of concrete pavement, and causes difficulty in finishing. On the other hand, a high pavement with high bleeding rate results in a pavement with low surface strength and abrasion resistance. According to the results demonstrated in Figure 4.17 (b), by the increase of rubber content bleeding percentage reduced. It was observed that introducing 30% or more rubber into concrete mixes resulted in bleeding lower than 1.5%. This indicated that there may be a difficulty with the surface finishing of the rubberised concrete prepared with 30% rubber content or more. In addition, it was revealed that introducing rubberised mix series prepared with 40% rubber content had 20% lower bleeding compared to the control samples (Figure 4.17 (b)). This effect might be the result of substituting a portion of aggregates with rubber particles, which are considered as impermeable constituents. In addition, according to the results demonstrated in Figure 4.18 for mix series with the same 28-day characteristic compressive strength of 32 MPa, mix series contained rubber had lower bleeding index.

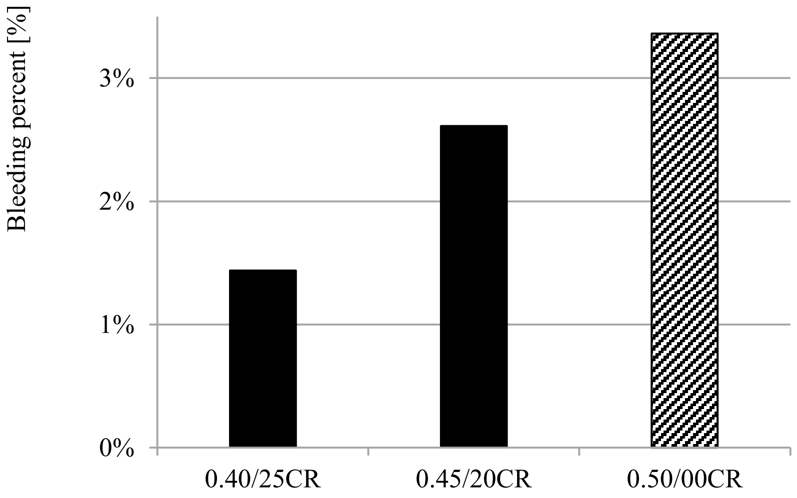


Figure 4.18: The bleeding index of samples with the same 28day strength of 32MPa

The impermeable property of rubber might prevent migration of the free water to the top surface of concrete. In addition, it was reported by Singh (2013) that using an air entraining agent results in higher air content and lowers the concrete bleeding. On the basis of this fact, the effect rubber on the increase of concrete air content (Figure 4.17) can reduce bleeding. The higher air content, results in more internal voids within the concrete matrix, which trap free water from migration to the surface of concrete. It is important to take into account that both high and low bleeding rates negatively affect concrete pavements. For conventional concrete pavements, a low bleeding rate might lead to a fast drying out of the top surface of concrete, which results in plastic shrinkage cracks. On the contrary, limiting concrete bleeding to a certain maximum level of 3% increases its wear resistance. It should be taken into account that only considering concrete bleeding properties is not enough and other effects of rubber on shrinkage properties of concrete should also be taken into account before drawing any conclusions regarding the positive or negative effect of introducing rubber to concrete pavements.

Mass per Unit Volume

Referring to Figure 4.19 mass per unit volume (MPV) decreased by the increase in rubber content. It indicated that the mix series with lower WC had higher MPV, whereas the mix series with lower WC had higher AC.

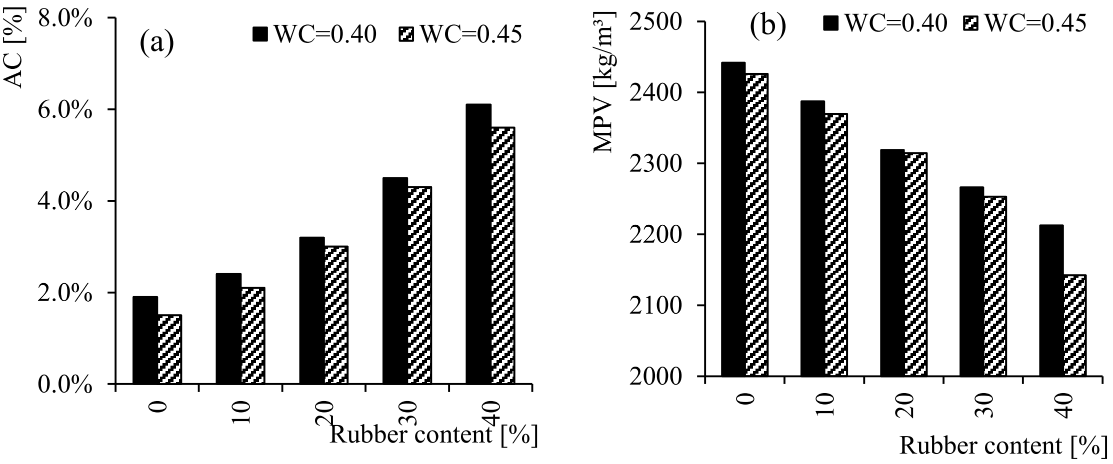


Figure 4.19: (a) AC and (b) MPV of mix series vs. different rubber contents

The higher MPV of mix series with WC of 0.40 was not because of the lower AC, but it was the result of less water and more aggregate content of these mix series. It was observed that roughly for each 10% increase (≈30 kg/m^3) in rubber content there was a 2.5% (≈60kg/m^3) decrease in the unit weight of CRC.

4.4.2 Test Results and Discussion on Hardened Properties

Generic mechanical hardened properties of pavement concrete are dependent on both of the raw materials and concrete production procedure (Neville & Brooks 2010; Mehta et al. 2006). Therefore, it was anticipated that applying water-soaked treatment affected both fresh and hardened properties of concrete.

Compressive Strength

The compressive tests were performed at the specified ages (i.e. 3, 7, 14, 21, 28, and 56 days). Compressive strength test results at different testing ages are demonstrated in Table 4.11. Referring to Figure 4.20 for the mixes with 30% and 40% of rubber content a change in the pattern of strength gain was observed.

Table 4.11: Compressive test results at different testing ages (3 to 56-day)

Mix ID	f_{cm} [MPa]						$f'_{c,28}$ [MPa]
	$f_{cm,3}$	$f_{cm,7}$	$f_{cm,14}$	$f_{cm,21}$	$f_{cm,28}$	$f_{cm,56}$	
M/0.40/00CR	33.1±1.6	50.5±3.6	55.9±2.7	60.8±2.8	63.0±3.3	71.6±2.4	57.6
M/0.40/10CR	30.2±1.6	44.8±1.8	48.9±1.2	52.5±1.6	54.1±0.8	60.8±3.0	52.9
M/0.40/20CR	25.8±1.1	32.8±1.7	38.9±2.0	42.7±1.9	44.3±1.2	46.8±1.4	42.3
M/0.40/30CR	20.1±1.3	27.8±1.2	29.2±1.3	29.4±1.1	30.9±1.3	32.4±0.9	28.8
M/0.40/40CR	16.7±0.8	20.8±1.5	22.5±1.8	22.7±0.5	22.9±0.6	23.4±0.6	21.8
M/0.45/00CR	29.2±1.4	45.3±3.2	50.5±2.0	53.3±1.7	55.6±2.0	63.1±3.0	52.2
M/0.45/10CR	25.7±1.2	35.4±3.3	40.1±2.6	43±2.2.0	45.8±2.0	47.3±0.5	42.5
M/0.45/20CR	21.0±1.1	27.6±1.5	30.6±1.1	33.5±1.0	34.9±1.3	37.5±0.4	32.8
M/0.45/30CR	17.5±1.1	21.8±1.7	22.9±1.7	23.9±1.5	23.8±1.0	27.5±1.2	22.1
M/0.45/40CR	12.6±0.3	16.5±0.5	17.0±0.5	17.4±0.4	18.2±0.4	21.8±0.7	17.6
M/0.50/00CR	22.0±0.7	32.4±2.1	36.5±2.4	38.6±2.5	39.3±1.9	40.7±1.8	36.1
M/0.55/00CR	15.5±1.1	23.1±1.4	26.4±1.8	28.0±2.4	30.2±1.7	30.9±2.0	27.5

The gaining strength curve has a logarithmic pattern with respect to the concrete age. However, for CRC contained 30% and 40% of crumb rubber, this pattern turned to a flattened line, which means for high contents of rubber rubberised concretes do not gain noticeable strength over time. It can be concluded that high volume of rubber content reduces both the compressive strength and the strength gain over time.

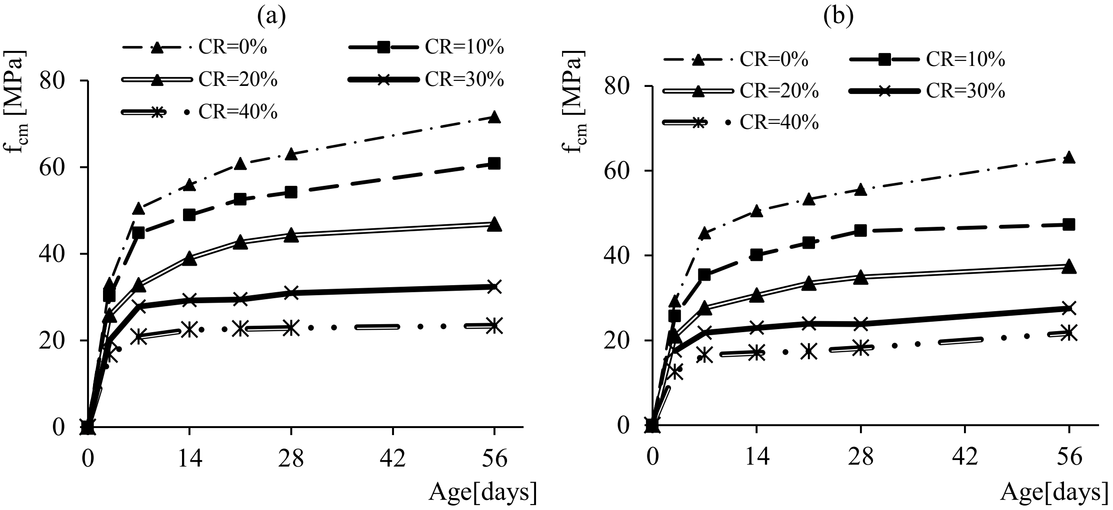


Figure 4.20: Effect of aging on compressive strength of CRC (a) WC=0.40, (b) WC=0.45

The CRC test results revealed that the concept of making a lighter, but relatively stronger concrete was not valid. Although introducing rubber into the mix makes the modified concrete lighter, the negative impact of rubber on compressive strength was evident. According to data presented in Figure 4.21, it can be seen that, by increasing of rubber content, the ratio of strength to density decreased and the mentioned decreasing trend was true for all samples at all testing ages.

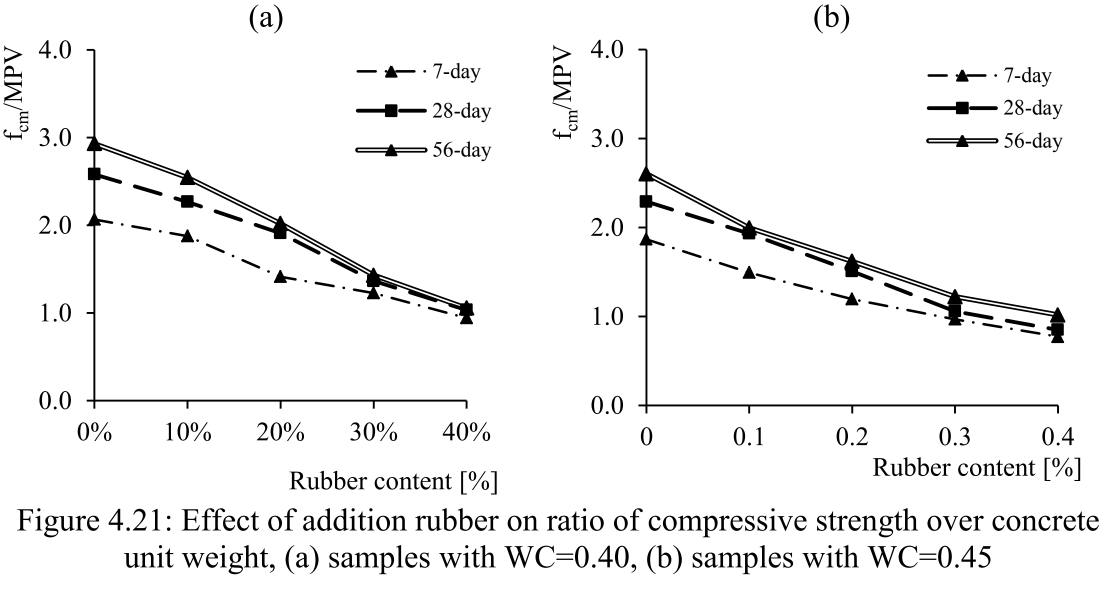


Figure 4.21: Effect of addition rubber on ratio of compressive strength over concrete unit weight, (a) samples with WC=0.40, (b) samples with WC=0.45

The failure of rubberised samples was found to be gradual without a total sudden collapse or a major crack. It was observed that rubberised concrete samples could hold themselves even after occurring of the failure cracks without shattering to pieces. Images from failed samples with 0%, 20% and 40% of rubber contents are demonstrated in Figure 4.22 (a, b and c). Unlike the plain concrete, there were not any major cracks found to be responsible for the failure. In contrast, a collective number of cracks together under the ultimate load resulted in failure of the rubberised samples.

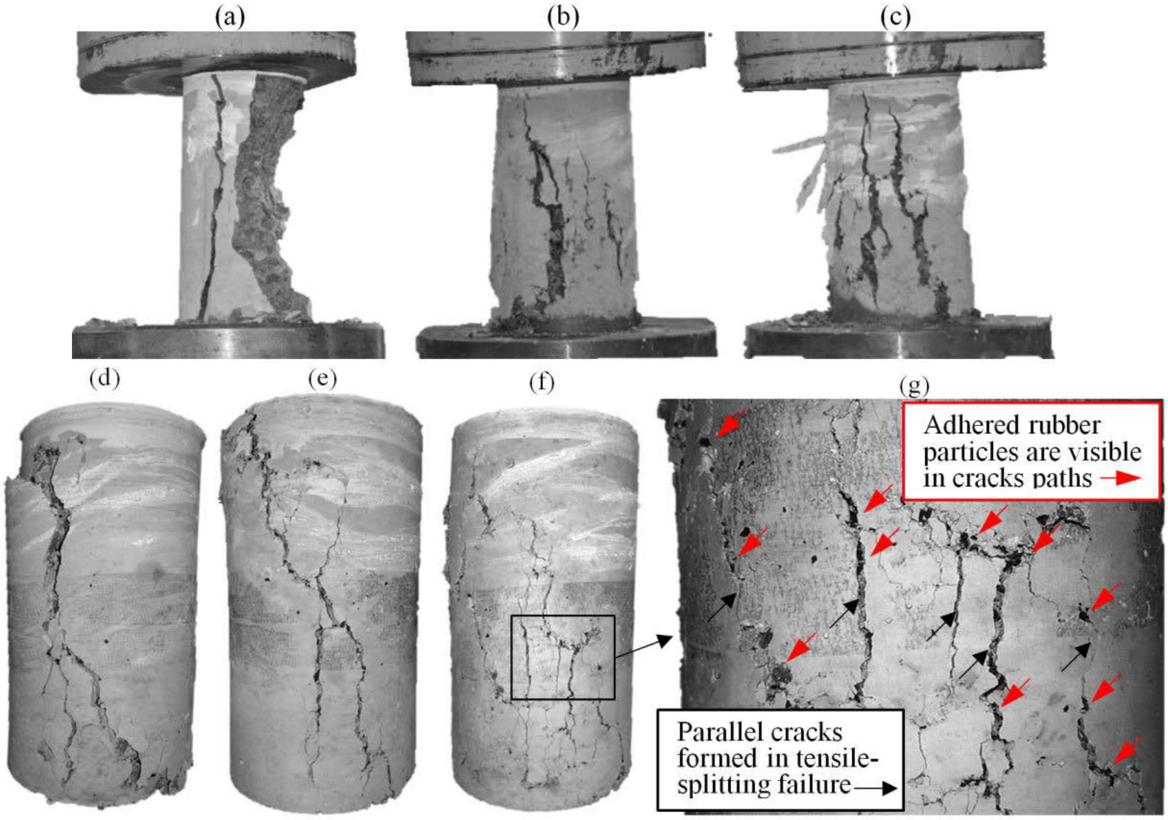


Figure 4.22: Effect of rubber on the concrete cracking and failure mode, (a and d) no rubber, the conical failure mode; (b and e) 20% rubber content, the conical-shear failure mode and (c, f and g) 40% rubber content, the splitting-tensile bottom and formation of parallel cracks

Failure of a concrete sample under a compressive load has different modes (Neville & Brooks 2010). A shear mode of failure occurs if the normal shear stress exceeds the shear strength of the paste, while the normal tensile stress is still lower than the tensile strength of samples. Test results showed that the CRC specimens under the compressive test exhibited a gradual shear failure mode if samples contained low or moderate content of rubber. In contrast, the splitting tensile failure patterns were observed for samples with high rubber content as presented in Figure 4.22 (d, e, f and g). As it can be seen from Figure 4.23, at low and moderate contents of rubber (10% to 20%) the rubber particles were placed separately in the concrete matrix, producing distributed spherical voids. In contrast, at high content of rubber (40% or more) rubber particles had higher chance to be placed close to each other and formed rubber to rubber connections, which results in making internal weak stress transfer regions (Khorrami et al. 2010). Consequently, this weak stress transfer regions were the source of crack propagation under stress, where the failure of CRC was accelerated.

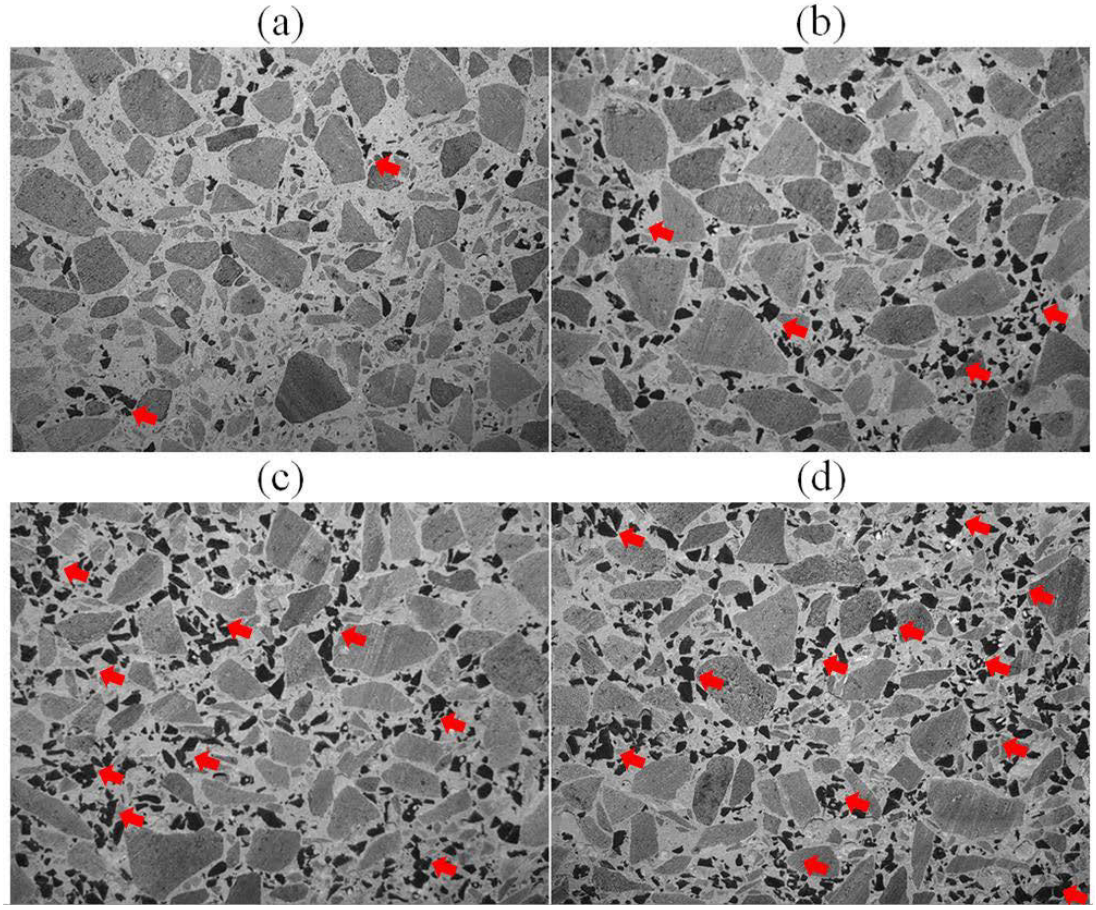


Figure 4.23: (a) 20% rubber content: scatter distribution of rubber particles throughout the concrete matrix, (b) 50%, (c) 60% and (d) 70% of rubber content: arrows show the higher rubber content results in the formation rubber-rubber connection

According to literature, the strength of rubberised concrete is a function of curing time, concrete constituents and rubber content. Previous studies provided some models for approximating the strength of rubberised concrete (Zheng et al. , Huo & Yuan 2008; Taha et al. 2009; Khatib & Bayomy 1999; Jingfu et al. 2008; Khaloo et al. 2008). However, these models were very preliminary and only considered the effect of rubber content on the concrete strength. For instance, some studies provided models based on a linear or polynomial trend line, which approximated the concrete strength only as a function of rubber content (Zheng et al. 2008; Taha et al. 2009). In addition, some other studies developed models based on strength reduction factor (Khaloo et al. 2008; Khatib

& Bayomy 1999). An indicator namely "Stress Reduction Factor (*SRF*)" was introduced based on the following equation:

$$SRF = \frac{f_{cmr}}{f_{cm}} \tag{4.1}$$

where f_{cmr} is the compressive or flexural strength of rubberised samples and f_{cm} is the compressive or the flexural strength of the control samples (prepared with no rubber).

Using *SRF* in approximation of the rubberised concrete strength has major limitations. The *SRF* factor is defined as a function of rubber and can be calculated only for an array of samples that have a same WC and are tested with the same duration of curing. As a consequence, *SRF* cannot be applied accurately for prediction of strength for different types of rubberised concrete with variety of WC ratios or for different time of testing.

This study introduced a model, which can be applied to approximate strength of rubberised concrete precisely. It can be seen that the strength of rubberised concrete is a function of curing time, concrete constituent and rubber content, which results in a strength function with three variables. In order to find a proper general and accurate pattern for this strength function, it is required to break down the strength function to its basic elements. This break down will result in simpler patterns, which make it possible to fit the pattern to the experimental data.

$$f_{cm}(t, WC, R) = u_{cm}(t) \times v_{cm}(WC) \times w_{cm}(R) \tag{4.2}$$

where f_c is the compressive strength of rubberised samples, t is curing time, WC is water-cement ratio, R is rubber content, $u_{cm}(t)$ is a function that correlate curing time to the concrete strength, $v_{cm}(WC)$ is a function that correlate water-cement ratio to the concrete strength and, $w_{cm}(R)$ is a function that correlate rubber content to the concrete strength.

Literature review of the previous studies, the proper pattern for each of the u, v and w functions were selected. According to the previous studies it was found that the best pattern that was fitted to the experimental data over the test period of 3 to 56 days was the model introduced by ACI 209R

$$f_{cm}(t) = \frac{t}{a+bt} \times f_{c28} \tag{4.3}$$

Where a and b are constants, f_{cm} is the strength of concrete in different testing time in MPa, f_{c28} is the 28-day compressive strength of concrete samples in MPa and t is time variable in day

In addition, in accordance to the literature different models are available for prediction of 28-day strength based on concrete constituents Popovics & Ujhelyi (2008), however, one of the most simple and the most accurate relationship is Abrams equation (Abrams 1919). It was found that the best pattern that was fitted to the experimental data with different WC ratios from 0.40 to 0.55 was the Abrams relationship.

$$f_{cm}(WC) = \frac{k_1}{k_2^{WC}} \tag{4.4}$$

Where k_1 and k_2 are constants, f_{cm} is the strength of concrete at 28-day test in MPa and WC is the mass ratio of water to cement.

Finally, considering only the effect of rubber on the strength of an array of concrete samples, it can be said that the relationship, which presents rubber effect is a polynomial relationship.

$$f_{cm}(WC,R) = f_{cm}(WC) \times \sum_{k=0}^{n} a_k (R - b_k)^k \tag{4.5}$$

Where k, a_k and b_k are constants, f_{cm} is the strength of rubberised concrete in MPa, $f_{cm}(WC)$ is the strength of control concrete at 28-day test in MPa and R is rubber content of mix in percentage.

Considering the presented three functions, the ultimate model for the strength of rubberised concrete can be rewrote as follows:

$$f_{cm}(t,WC,R) = \frac{t}{a+bt} \times \frac{k_1}{k_2^{WC}} \times \sum_{k=0}^{n} a_k (R - b_k)^k \tag{4.6}$$

where f_{cm} is the compressive strength of rubberised samples in MPa, t is age of samples kept in lime-saturated curing condition in day, WC is ratio of water mass to cement mass, R is rubber content in percentage, a, b, k_1, k_2, k, a_k and b_k are constants.

Table 4.12 provides information regarding both of the experimental results and results calculated based on the introduced model.

Table 4.12: Comparison of experimental data and the calculated results from the introduced model

WC ratio	0.40						0.45					0.50	0.55
Rubber content[%]	0	10	20	25	30	40	0	10	20	30	40	0	0
Curing time [day]	Experimental compressive test results												
Strength at 3 days of curing [MPa]	33.1	30.2	25.8	23.3	20.1	16.7	29.2	25.7	21.0	17.5	12.6	22.0	16
Strength at 7 days of curing [MPa]	50.5	44.8	32.8	29.2	27.8	20.8	45.3	35.4	27.6	21.8	16.5	32.4	23
Strength at 14 days of curing [MPa]	55.9	48.9	38.9	34.5	29.2	22.5	50.5	40.1	30.6	22.9	17.0	36.5	26
Strength at 21 days of curing [MPa]	60.8	52.5	42.7	36.6	29.4	22.7	53.3	43.0	33.5	23.9	17.4	38.6	28
Strength at 28 days of curing [MPa]	63.0	54.1	44.3	35.9	30.9	22.9	55.6	45.8	34.9	23.8	18.2	39.3	30
Strength at 56 days of curing [MPa]	71.6	60.8	46.8	38.8	32.4	23.4	63.1	47.3	37.5	27.5	21.8	40.7	31
Curing time [day]	Approximated results based on formula												
Strength at 3 days of curing [MPa]	34.1	30.6	26.5	24.2	21.6	15.7	26.4	23.7	20.5	16.7	12.1	20.5	16
Strength at 7 days of curing [MPa]	49.2	42.8	35.8	32.1	28.1	19.5	38.1	33.2	27.8	21.8	15.1	29.5	23
Strength at 14 days of curing [MPa]	59.0	50.4	41.3	36.5	31.7	21.4	45.7	39.0	32.0	24.5	16.6	35.4	27
Strength at 21 days of curing [MPa]	63.2	53.5	43.5	38.3	33.1	22.2	48.9	41.5	33.7	25.6	17.2	37.9	29
Strength at 28 days of curing [MPa]	65.5	55.2	44.7	39.3	33.8	22.6	50.7	42.8	34.6	26.2	17.5	39.3	30
Strength at 56 days of curing [MPa]	69.3	58	46.6	40.8	35.0	23.2	53.7	45.0	36.1	27.1	18.0	41.6	32
Curing time [day]	Error in Approximation												
Error of estimation at 3-day test [%]	3%	1%	3%	4%	7%	6%	9%	8%	2%	4%	3%	15%	2%
Error of estimation at 7-day test [%]	3%	4%	9%	10%	1%	6%	16%	6%	1%	0%	9%	9%	1%
Error of estimation at 14-day test [%]	6%	3%	6%	6%	8%	5%	10%	3%	5%	7%	2%	3%	4%
Error of estimation at 21-day test [%]	4%	2%	2%	5%	12%	2%	8%	4%	1%	7%	1%	2%	5%
Error of estimation at 28-day test [%]	4%	2%	1%	9%	9%	1%	9%	7%	1%	10%	4%	0%	1%
Error of estimation at 56-day test [%]	3%	5%	0%	5%	8%	1%	15%	5%	4%	1%	18%	2%	4%
Total result	Average error is 5.1% and STDV Error is 3.9%												

It can be seen that the “a” parameter in ACI 209R relationship, itself is a function of rubber content. Using curve-fitting tool in MATLAB software, the introduced patterns was fitted to the experimental data and the required constants were found as shown in relationship (4.7)

$$f_{cm}(t,WC,R) = \frac{t}{(\text{-}4.283\text{R} + 3.12) + 0.9t} \times \frac{510.301}{165.009^{WC}} \times (-1.691R + 1.0005) \tag{4.7}$$

where f_{cm} is the compressive strength of rubberised samples in MPa, t is curing time in day, WC is ratio of water mass to cement mass, R is rubber content in percentage

Combining the provided equation (4.7) the developed equation can be rewritten as follows

$$f_{cm}(t,WC,R) = \frac{(510.556 - 862.919R) \times t}{165.009^{WC}\,(0.9t \text{ - } 4.283\text{R} + 3.12)} \tag{4.8}$$

where f_{cm} is the compressive strength of rubberised samples in MPa, t is curing time in day, WC is ratio of water mass to cement mass, R is rubber content in percentage

Using the provided equation the strength of rubberised samples with different water cement ratios and at different ages and rubber content could be approximated by insignificant error of only 5% averagely. Equation (4.9) presenting the shape function to be fitted to experimental results of rubberised concrete.

$$f_{cm}(t,WC,R) = \frac{(A - B \times R) \times t}{C^{WC}\,(D \times t \text{ - } \text{E} \times \text{R} + \text{F})} \tag{4.9}$$

where f_{cm} is the compressive strength of rubberised samples in MPa, t is curing time in day, WC is ratio of water mass to cement mass, R is rubber content in percentage and A, B, C, D, E and F are constants will be determined using curve-fitting software.

For any specific mix-design it is required to adjust constant values of A to F based on the mix constituent’s properties. The proposed method for determining parameters A to F in Equation (4.9) is to check the experimental data of given mix without rubbers to that equation in the first stage. Then when constants A to F were calculated based on the test results of plain concrete, the adjusted equation would be used for approximating the strength of rubberised concrete with a variety content of rubber.

Modulus of Rupture

Flexural tests were performed at the specified ages (i.e. 7, 28, and 56 days). The Flexural test results at different testing ages are demonstrated in Table 4.13. Experimental results confirmed that presence of rubber particles acted as a hole at flexural cracks tips. Therefore, the tip sharpness of cracks decreases by introducing rubber particles (as shown in Figure 4.27). Literature addressed that tyre rubber is considered a soft material and can perform as a barrier against the crack growth in concrete (Khorrami et al. 2010). Experimental results indicated that the cracks were prevented from propagation, by slowing down the kinetics of the first crack's propagation.

Table 4.13: Flexural test results at different testing ages (7 to 56-day)

Mix ID	Flexural strength (MOR) [MPa]		
	$f_{ctm,7}$	$f_{ctm,28}$	$f_{ctm,56}$
M/0.40/00CR	6.1±0.14	6.9±0.23	7.2±0.29
M/0.40/10CR	5.4±0.26	6.2±0.25	6.7±0.20
M/0.40/20CR	4.8±0.18	5.6±0.25	5.8±0.10
M/0.40/30CR	4.3±0.16	5.2±0.14	5.6±0.14
M/0.40/40CR	3.9±0.11	4.6±0.12	4.6±0.06
M/0.45/00CR	5.4±0.20	6.0±0.25	6.0±0.04
M/0.45/10CR	4.7±0.25	5.4±0.11	5.6±0.13
M/0.45/20CR	4.2±0.13	5.0±0.22	5.3±0.33
M/0.45/30CR	3.6±0.21	4.1±0.17	4.3±0.29
M/0.45/40CR	3.0±0.08	3.6±0.17	3.7±0.07
M/0.50/00CR	3.9±0.11	4.9±0.22	5.0±0.22
M/0.55/00CR	3.4±0.14	4.2±0.21	4.4±0.28

The ratio of the flexural strength to the compressive strength (f_{ctm}/f_{cm}) is another influential index, the greater of the ratio in the concrete, the stronger resistance against the tensile crack (Kang & Jiang 2008). It was observed that, introduction of rubber had more negative impact on the compressive strength than that on the flexural strength of rubberised concrete. Referring to Figure 4.24, it can be seen for each 10% (≈30 kg/m^3) increase in rubber content, the compressive strength was reduced 17% while that rate was 8% for the flexural strength. As expected, mix with WC of 0.45 had lower *SRF* with the same content of rubber, which means the negative effect of containing higher rubber content on the compressive strength was higher for WC of 0.45 compared to

0.40. In addition, results demonstrate the uniform effect of rubber content on strength reduction over the increase of rubber content up to 40%.

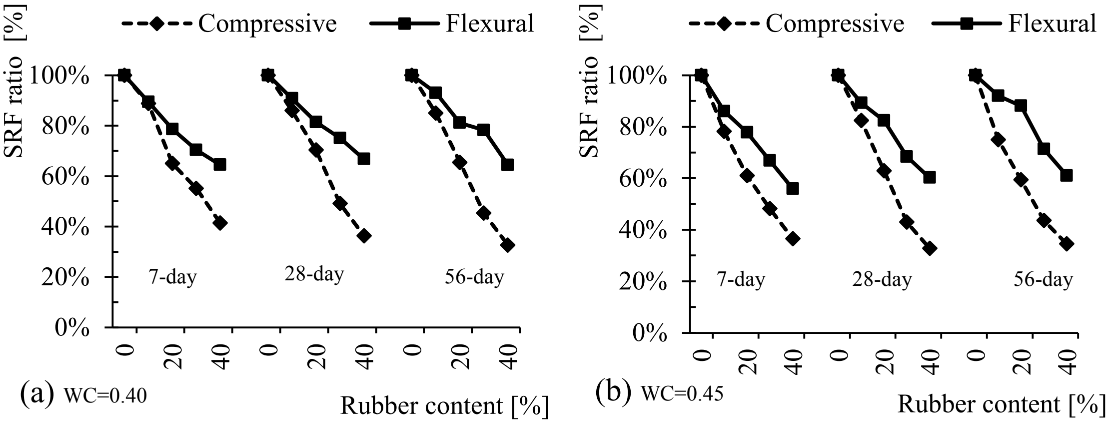


Figure 4.24: Ratio of compressive and flexural strength to the control samples (a) WC=0.40 and (b) WC=0.45

The flexural stress is the most important stress that pavement undergoes. The ratio of flexural to compressive strength (f_{ctm}/f_{cm}) is an important index for pavement concrete, which means, the greater of the ratio, the stronger of concrete to resist tensile flexural crack. An increase in the ratio shows the improvement in flexural strength for the concrete with the same compressive strength. Results in Figure 4.25 represent a significant increase in the ratio by increasing rubber content. It can be concluded that, for same strength grade samples, higher rubber content results in higher flexural strength.

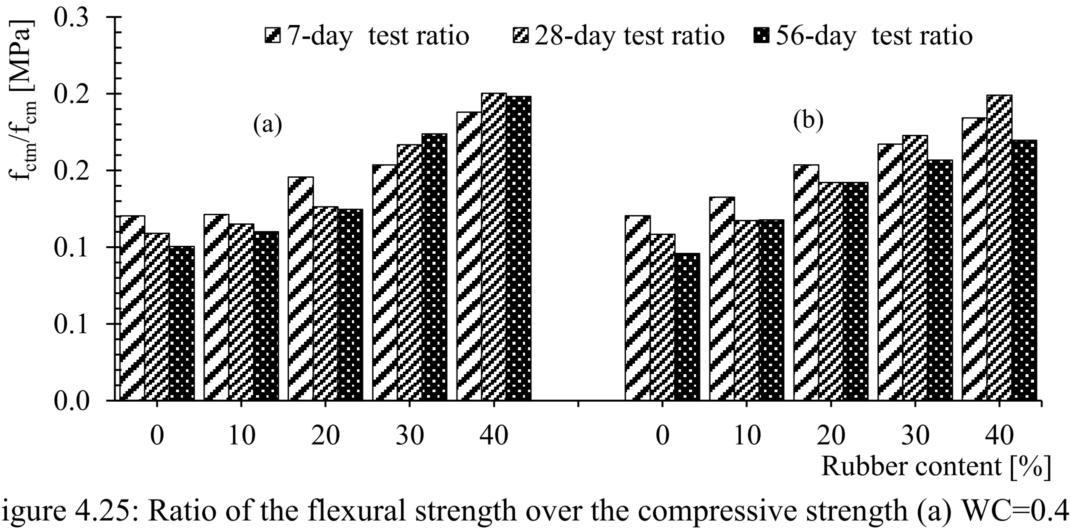


Figure 4.25: Ratio of the flexural strength over the compressive strength (a) WC=0.40, (b) WC=0.45

The ultimate tensile strain capacity of pavement concrete was assessed if any improvement achieved regarding the increase in the strain at the failure. For all flexural samples, LVDT measures were set in mid-span point of the samples, in order to measure the deflation of samples under load. Samples with higher deflection are more ductile and can resist higher flexural strain before failure.

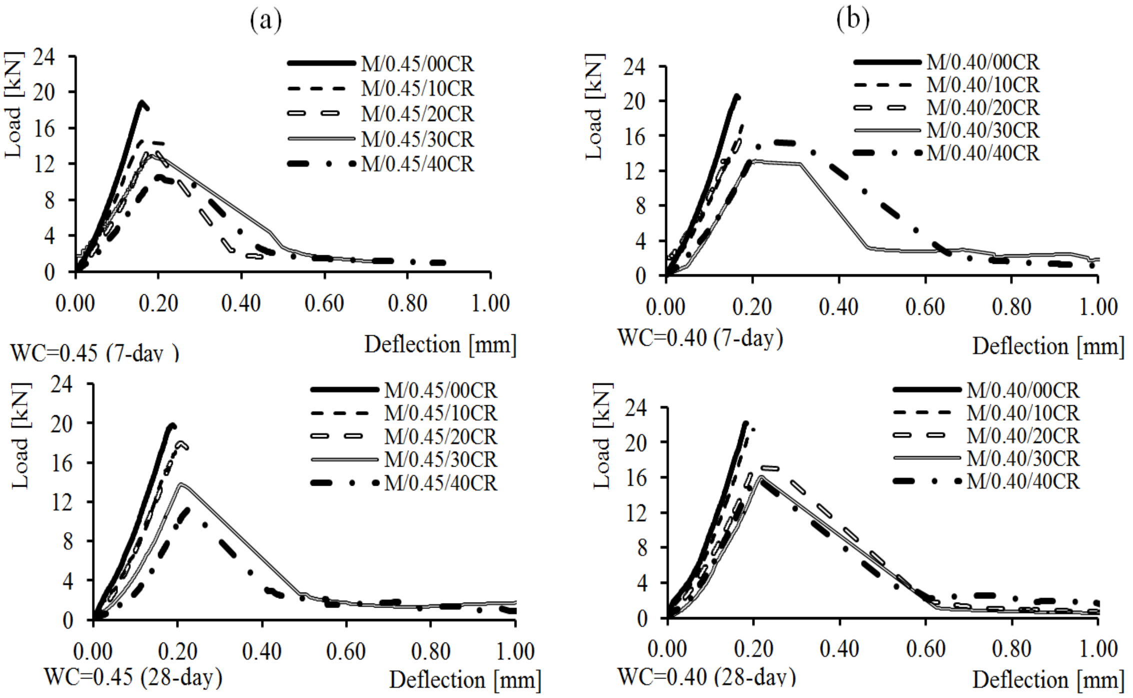


Figure 4.26: Flexural deflection of samples at (a) WC=0.40, (b) WC=0.45

Figure 4.26 demonstrates the load-deflection results of CRC for two ages, 7 and 28 days. For different ages, the mid-span deflections at the maximum flexural loads were recorded and compared with the control sample without rubber.

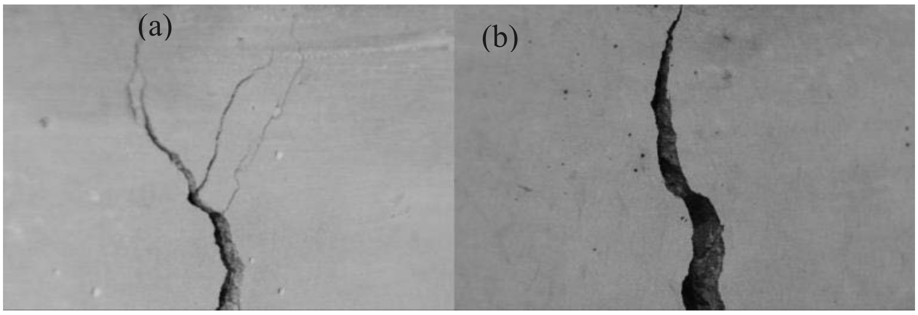


Figure 4.27: Crack propagation in concrete samples (a) gradual crack propagation and no sharp tip of crack of rubberised concrete sample with 30% rubber content, (b) typical cracking propagation pattern of plain concrete samples with a sharp crack tip

Results revealed a significant improvement in the strain capacity of the produced rubberised concrete by increasing the rubber content. Moreover, results showed that the strain capacity was not changed significantly by the age of concrete.

Failure pattern of flexural samples was observed during this experimental program. It was found that samples without rubber or samples with low volume (10%) of rubber content had a sudden failure under the ultimate load by initiation of the first crack (Figure 4.27).

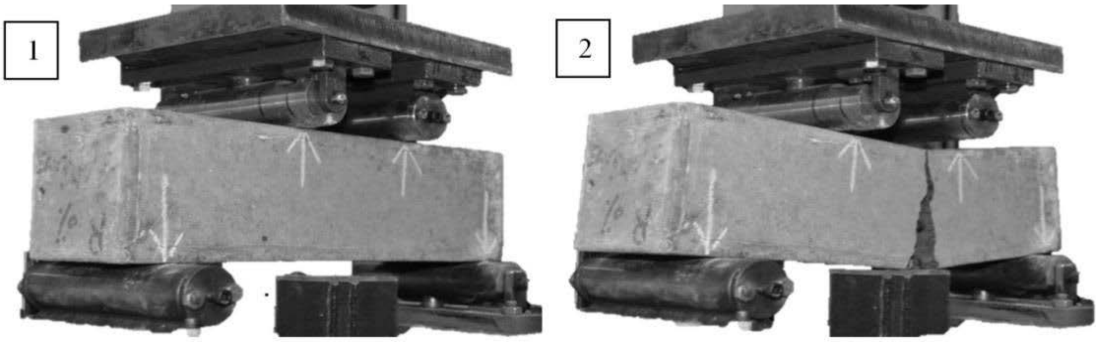


Figure 4.28: Typical sudden failure of samples without rubber under the ultimate load

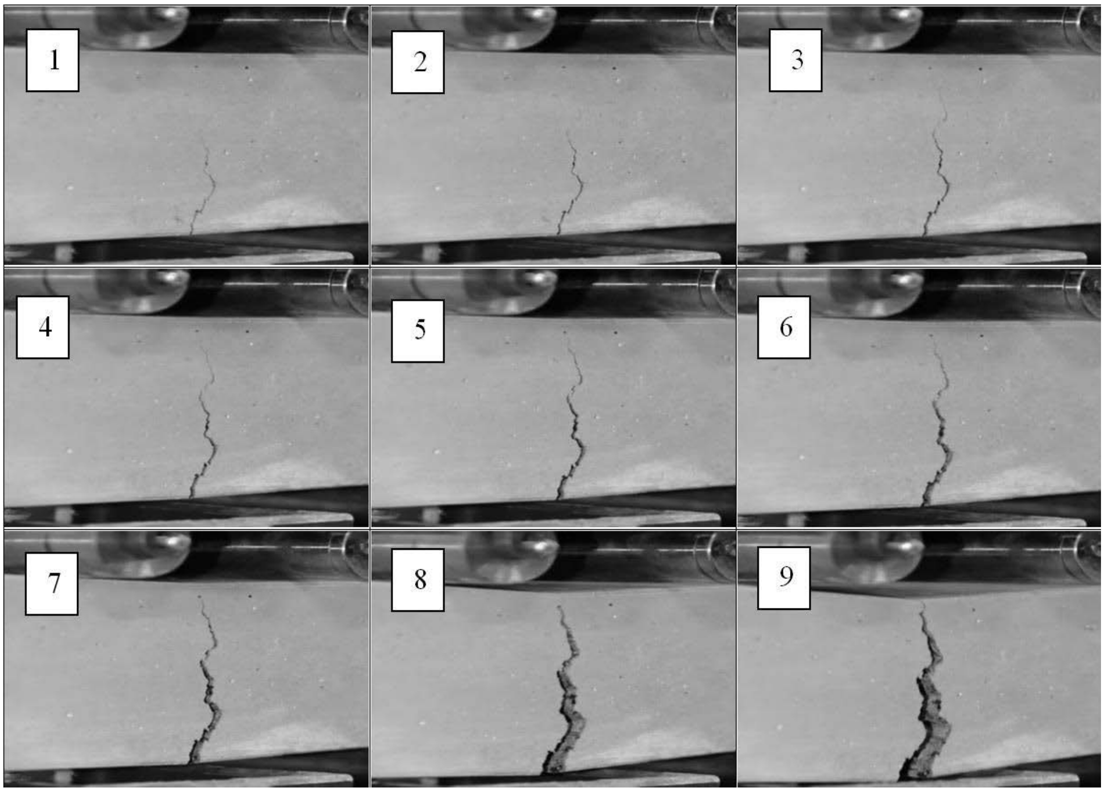


Figure 4.29: (1 to 9) Cracking pattern of a sample with 20% rubber content, showing very slow crack propagation under the ultimate load

This observation also revealed that samples without rubber or samples with a low volume of rubber content (10%) had a sudden failure under the ultimate load by initiation of the first crack (Figure 4.28). In contrast, samples with higher content of rubber presented gradual failure with a gradual propagation of crack from the bottom of samples to the top (Figure 4.29).

Modulus of Elasticity

Static chord modulus of elasticity of CRC at 7, 28 and 56 days were determined and summarised in Table 4.14. A greater difference in MOE was observed over a period of 56 days between the control and the CRC at 56-day of age compared to the 28-day test results. It means that the stiffness and brittleness of CRC in long-run is much less compared with plain concrete. The MOE is a function of the compressive strength of concrete. A high difference between 56 day MOE of plain concrete and rubberised concrete supported the outcome of compressive test results, showing the negative impact of rubber on concrete strength gain over time.

Table 4.14: Elastic modulus at 7, 28 and 56 days for different WC and rubber contents

Mix reference	$E_{c,7}$ [GPa]	$E_{c,28}$ [GPa]	$E_{c,56}$ [GPa]
M/0.40/00CR	42.4	46.5	48.4
M/0.40/10CR	38.9	42.8	45.3
M/0.40/20CR	34.8	37.4	39.7
M/0.40/30CR	30.4	33.4	35.4
M/0.40/40CR	28.1	29.9	30.8
M/0.45/00CR	39.4	42.3	43.6
M/0.45/10CR	34.1	37.5	39.0
M/0.45/20CR	32.4	34.5	35.2
M/0.45/30CR	29.5	30.5	31.0
M/0.45/40CR	26.0	26.3	25.6
M/0.50/00CR	37.0	39.4	41.0
M/0.55/00CR	32.4	34.5	35.5

It can be noted that addition of rubber had a significant effect on stress relaxation of concrete and changed the characteristics of concrete material from a brittle to a ductile product. It was illustrated that two mixes with the same compressive strength, mixes contained crumb rubber had lower elastic modulus. As a consequence, it can be concluded that, for samples with the same compressive strength, the better performance regarding flexural strength and modulus of elasticity can be achieved by higher content of rubber. The higher flexural strength and lower elastic modulus were observed for the modified concrete with rubber compared to the same strength concrete, which does not contain rubber. These properties are favourable for pavement concrete.

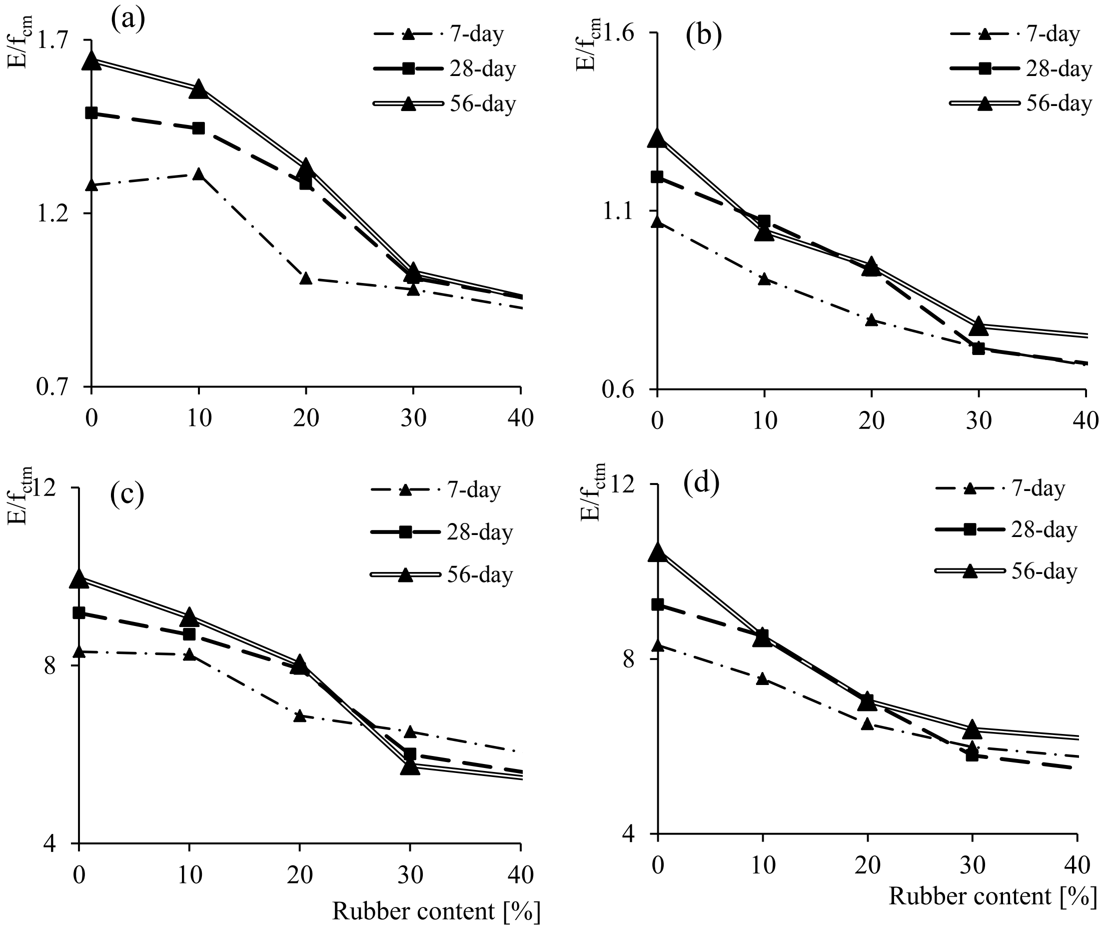


Figure 4.30: Ratio of modulus of elasticity (a) over compressive strength, WC=0.45, (b) over compressive strength, WC=0.40, (c) over flexural strength, WC=0.45, (d) over flexural strength, WC=0.40,

Although plain concrete with WC of 0.50 had same compressive strength with the rubberised mixes with WC ratio of 0.45 and 0.40, the rubberised mixes had higher flexural strength and lower modulus of elasticity, which indicates a significant improvement in mechanical characteristics of rubberised concrete for pavement application. It can be observed from Figure 4.30 that the ratio of elastic modulus over both flexural and compressive strengths is decreasing by introducing of rubber into concrete. This means that the rate of decrease in the elastic modulus is much higher than the rate of decrease in strength for all ages. The produced CRC is a more relax and less sensitive to the applied external strain for all ages of concrete.

Cyclic Loading (Fatigue)

The results of the cyclic tests are listed in Table 4.15. Results demonstrated in Figure 4.31 indicate that modification of concrete with crumb rubber had a positive effect on fatigue behaviour of concrete pavement.

Table 4.15: Cyclic test results for different mix series at the age of 56 days

Mix Reference	f_{ctm} [kN]	σ_{ctm} [MPa]	$0.05\sigma_{ctm}$ [MPa]	$0.75\sigma_{ctm}$ [MPa]	$0.9\sigma_{ctm}$ [MPa]	*Number of cycles at* $0.75\times\sigma_{ctm}$	*Number of cycles at* $0.90\times\sigma_{ctm}$
M/0.40/00CR	25.1	7.2	0.36	5.40	6.48	1000	360
M/0.40/10CR	22.8	6.7	0.34	5.03	6.03	1000	288
M/0.40/20CR	19.0	5.8	0.29	4.35	5.22	1000	275
M/0.40/30CR	17.8	5.6	0.28	4.20	5.04	1000	325
M/0.40/40CR	16.2	4.6	0.23	3.45	4.14	1000	330
M/0.45/00CR	19.9	6	0.30	4.50	5.40	1000	460
M/0.45/10CR	18.8	5.5	0.28	4.13	4.95	1000	333
M/0.45/20CR	18.3	5.3	0.27	3.98	4.77	1000	338
M/0.45/30CR	14.1	4.3	0.22	3.23	3.87	1000	427
M/0.45/40CR	12.8	3.7	0.19	2.78	3.33	1000	495

Introducing rubber at low content of 10% had an adverse impact on the mixes and reduced the number of cycles that concrete could resist against the cyclic load. However, addition of more rubber improved the resistance of samples against the cyclic load as demonstrated.

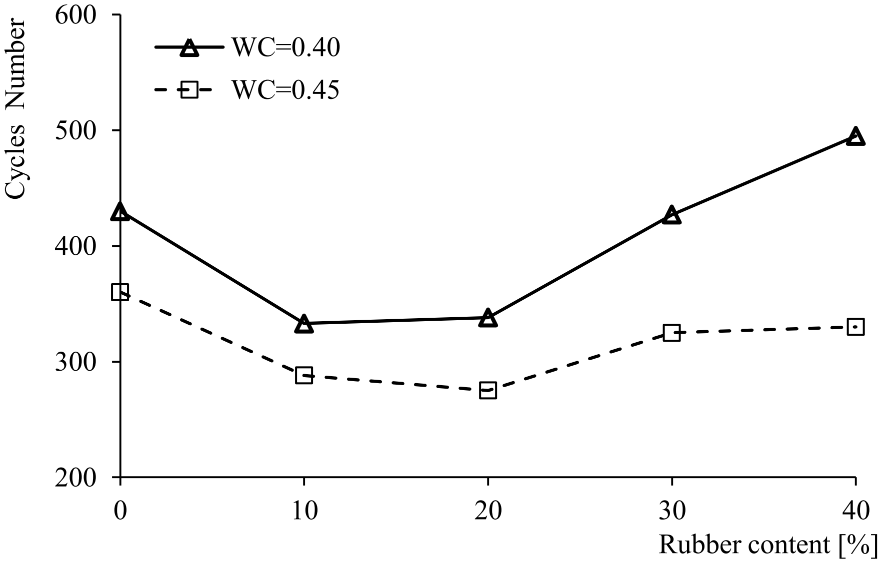


Figure 4.31: Numbers of cycles before failure of samples

Toughness

As can be seen from toughness test result shown in Table 4.16, introducing rubber into concrete mix enhanced the concrete toughness. It was observed that samples with WC ratios of 0.40 and 0.45, which did not contain rubber, had very low toughness. However, the enhancement in toughness properties of rubberised concrete samples was found insignificant, mostly because of low residual load capacity after the first peak. The most significant observed enhancements were the large deflection of samples under the load. In addition, rubberised samples demonstrated a high resistance against a sudden splitting failure also quick propagation of cracks through the concrete matrix structure.

Table 4.16: Toughness results conducted in accordance with the Standard ASTM C1609

Mix ID	Dimension		$\delta_P = \delta_1$ [1]			$\delta_{L/600}$=0.50mm [2]		$\delta_{L/600}$=0.50mm [3]		Toughness	
	b [mm]	d [mm]	δ [mm]	P_P [kN]	$f_P = f_1$ [MPa]	$P^D{}_{600}$ [kN]	$f^D{}_{600}$ [MPa]	$P^D{}_{150}$ [kN]	$f^D{}_{150}$ [MPa]	$T^D{}_{150}$ [J]	$R^D{}_{150}$ [%]
0.40/00CR	101.8	99.6	0.17	22.34	6.64	0.00	0.00	0.00	0.00	1.93	4.32
0.40/00CR	100.3	99.8	0.12	22.93	6.89	0.00	0.00	0.00	0.00	1.42	3.10
0.40/00CR	101.1	99.5	0.14	23.92	7.17	0.00	0.00	0.00	0.00	1.71	3.57
Average: 0.40/00CR											**3.66**
0.40/25CR	97.2	102.1	0.18	16.59	4.91	0.94	0.28	0.57	0.17	2.84	8.56
0.40/25CR	101.1	100.7	0.19	17.10	5.00	0.97	0.28	0.59	0.17	2.90	8.48
0.40/25CR	100.5	101.1	0.21	17.87	5.22	0.97	0.28	0.60	0.18	3.20	8.95
Average: 0.40/25CR											**8.66**
0.40/40CR	99.7	97.8	0.27	14.79	4.65	3.88	1.22	0.31	0.10	5.47	18.49
0.40/40CR	100.3	98	0.26	15.08	4.70	3.93	1.22	0.33	0.10	5.66	18.77
0.40/40CR	100.7	98.1	0.28	15.38	4.76	4.06	1.26	0.33	0.10	5.92	19.25
Average: 0.40/40CR											**18.84**
0.45/00CR	100.4	102.4	0.28	21.47	6.12	0.00	0.00	0.00	0.00	3.20	7.45
0.45/00CR	99.8	99.9	0.29	22.43	6.75	0.00	0.00	0.00	0.00	3.29	7.34
0.45/00CR	101.4	100.1	0.29	22.75	6.72	0.00	0.00	0.00	0.00	3.34	7.34
Average: 0.45/00CR											**7.38**
0.45/20CR	99.9	101.8	0.25	15.86	4.60	3.94	1.14	0.49	0.14	5.88	18.54
0.45/20CR	101.4	98.4	0.29	16.43	5.02	3.95	1.21	0.50	0.15	5.12	15.58
0.45/20CR	99.5	99.7	0.28	16.60	5.04	4.15	1.26	0.50	0.15	5.35	16.11
Average: 0.45/20CR											**16.74**
0.45/40CR	98	101.4	0.24	12.21	3.64	0.59	0.18	2.15	0.64	3.66	14.99
0.45/40CR	99.6	99.4	0.3	12.74	3.88	0.62	0.19	2.17	0.66	4.01	15.74
0.45/40CR	100.4	99.1	0.33	13.10	3.99	0.63	0.19	2.20	0.67	5.30	20.22
Average: 0.45/40CR											**16.98**

[1] δ_P = net deflection at peak, δ_1 = net deflection at first peak, P_P = peak load, $f_P = f_1$ = peak strength

[2] $\delta_{L/600}$= 0.5mm net deflection, $P^D{}_{600}$= residual load at deflection of 0.5mm, $f^D{}_{600}$= residual strength at deflection of 0.5mm

[3] $\delta_{L/150}$= 2mm net deflection, $P^D{}_{150}$= residual load at deflection of 2mm, $f^D{}_{150}$= residual strength at deflection of 2mm

Islam (2012) applied loading rate in average 25 times lower than the ASTM1609, while in this research loading rate reduced only 10 times. The test results attained for the modified ASTM C1609 method did not show any significant difference compared to the first series of tests. The absence of any significant difference in results proved that lowering the loading rate of the standard test is not beneficial for rubberised concrete. In contrast, it made the test significantly time-consuming and difficult to be performed.

4.4.3 Test Results and Discussion on Shrinkage Properties

Plastic Shrinkage

The plastic and drying tests were conducted in accordance with the Standards AS1012.13 and ASTM C1579, respectively. The ASTM C1579 test was found to be the most suitable, considering the restraining friction of subbase that is applied to concrete pavements.

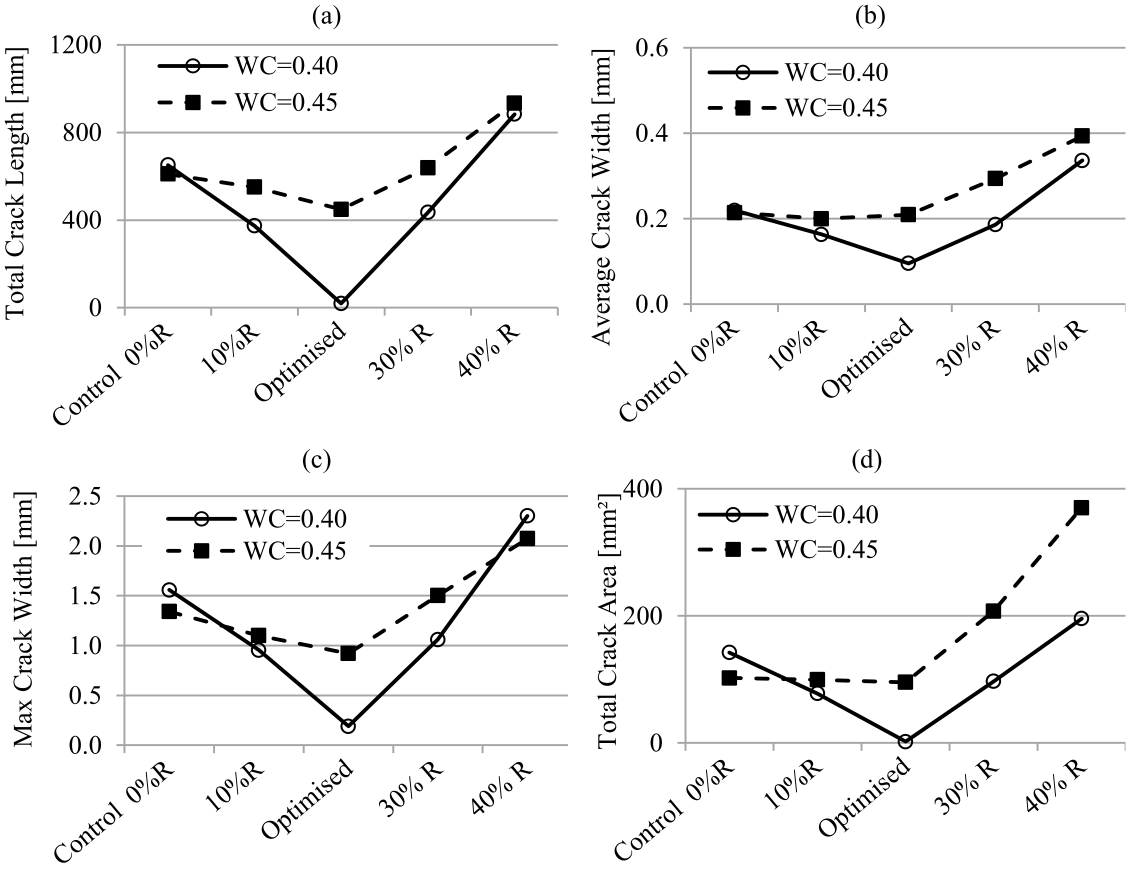


Figure 4.32: Different WC ratios and rubber content vs. (a) total crack length (b) average crack width (c) maximum crack width, (d) total crack area

As can be seen from Figure 4.32, there was an optimum point for rubber content, where the plastic shrinkage cracking was minimal. According to results presented in Figure 4.33, adding rubber up to 20%-25% provided a significant continuous improving effect on the resistance of concrete against plastic shrinkage. It was observed that up to 20%-25% rubber content, the average crack length, width and area were reduced for both of the concrete arrays with water-cement ratios of 0.40 and 0.45. On the contrary, it was found that introducing extra rubber than the 20%-25% content, cancelled out the achieved improving effects and by continuing the addition of rubber, shrinkage cracking properties of concrete negatively impacted and became even worse than the concrete without rubber. Test results indicated that there was a correlation between the minimum required strength of the rubberised concrete (32 MPa) and the lowest plastic shrinkage cracking of concrete. It can be noted that concrete samples, which had very high or very low strengths did not show satisfactory resistance against plastic shrinkage cracks.

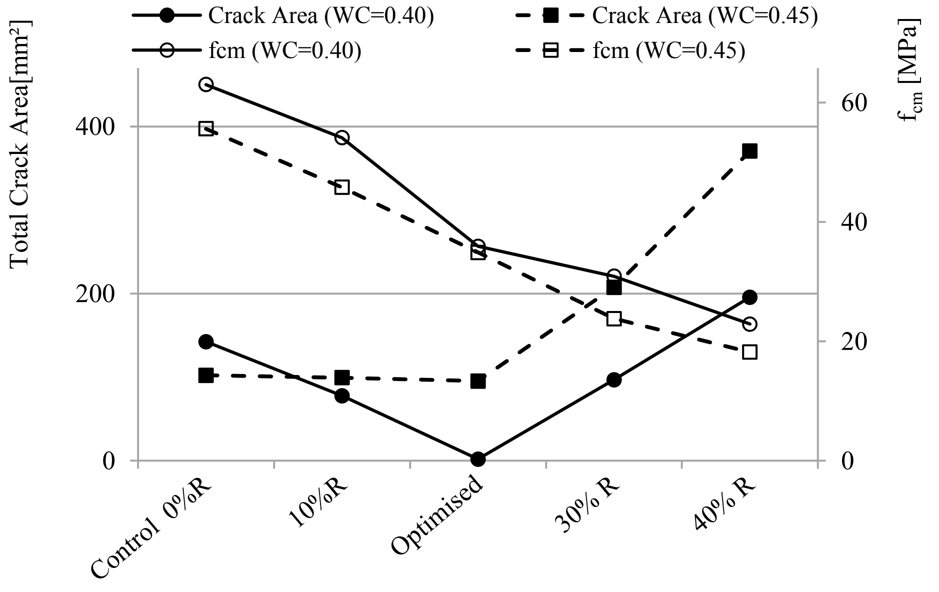


Figure 4.33: Total crack area and compressive strength vs. rubber content

Furthermore, a previous study discussed and recommended recording the time that the first crack occurs during the plastic shrinkage test (Sivakumar & Santhanam 2007). Subsequently, this analysis was accomplished and the results are presented in Figure 4.34 (a). The plotted results indicate that the time of first crack occurrence was significantly longer for the optimum content of rubber.

Standard ASTM C1579 introduced the crack reducing ratio (*CRR*), which is calculated according to Equation (4.10). This index is applied to quantify the amount of improvement in plastic shrinkage properties of modified concrete compared to the unmodified control concrete samples.

$$CRR = \left[1 - \frac{\text{Average Crack Width of Modified Concrete [mm]}}{\text{Average Crack Width of Reference Concrete [mm]}}\right] \times 100 \tag{4.10}$$

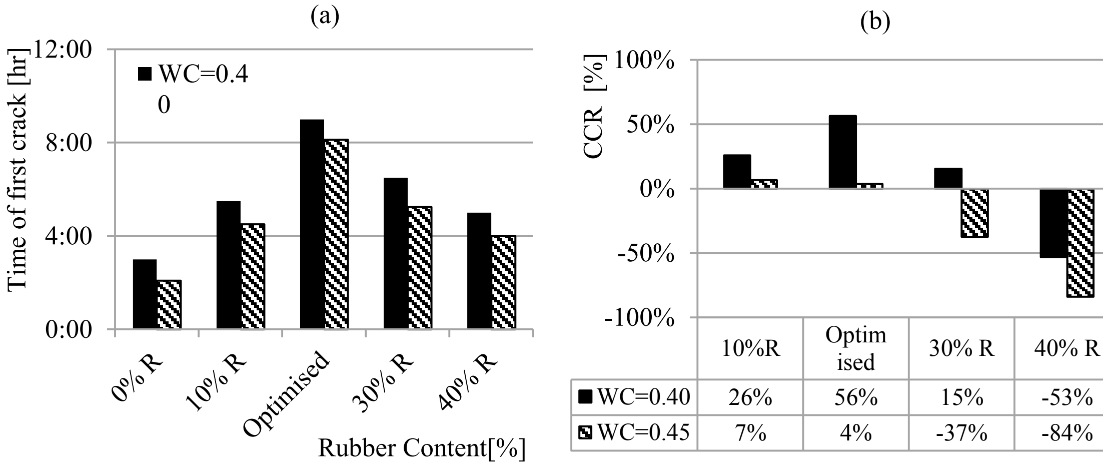


Figure 4.34: (a) Time the first crack observed on concrete slabs and (b) the calculated crack reducing ratio (*CRR*)

Results demonstrated in Figure 4.34 (b) revealed that rubberised concrete samples with the optimised rubber content showed the best shrinkage performance with high *CRR* value. In contrast, by introducing more rubber into concrete, the *CRR* decreased and turned to a negative value, which means it did not improve the resistance of concrete against shrinkage cracking.

Drying Shrinkage

It is a well-established fact that concrete samples with high WC ratios have higher drying shrinkage because they contain more unbound free water in mix (Holt & Leivo 2004). This idea was found valid for the rubberised concrete as shown in Figure 4.35 (a). Based on the results demonstrated in Figure 4.35 (a) it was confirmed that adding rubber into concrete mix series will result in the increase drying shrinkage for both the mix series with different WC ratios.

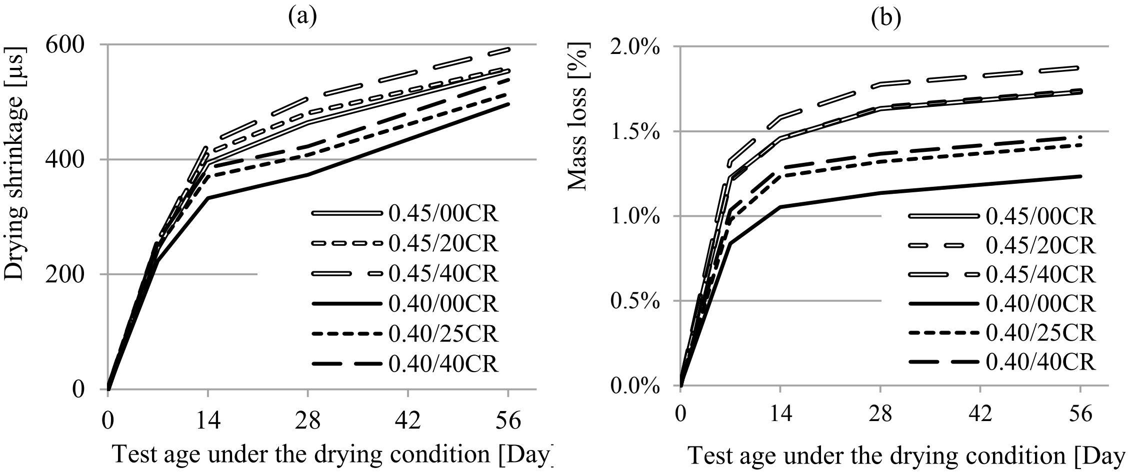


Figure 4.35: (a) The measured drying shrinkage and (b) The mass loss of samples kept in the standard drying condition

The highest drying shrinkage was observed for mix 0.45/40CR which was prepared with the highest rubber content and water-cement ratio. It was observed that by introducing 40% rubber content the drying shrinkage values at different ages were increased 5% to 15%. The achieved results were supported by previous studies (Bravo & de Brito 2012; Sukontasukkul & Tiamlom 2012), however, the 15% increase in drying shrinkage was lower than the reported values in the previously published papers. For instance there was 90% higher drying shrinkage reported by (Sukontasukkul & Tiamlom 2012) for rubberised concrete prepared with 30% rubber. Figure 4.35 (b) presents the change of “mass loss” parameter for concrete arrays over 56 days of drying condition. This parameter can be calculated using Equation (4.11).

$$Mass\ loss = 1 - \frac{Mass_{\ at\ age\ of\ T}}{Mass_{\ at\ age\ of\ 7th\ day}} \tag{4.11}$$

where, $Mass_{\ at\ age\ of\ T}$ is the samples mass at drying age of T in gram, $Mass_{\ at\ age\ of\ 7th\ day}$ is the surfaced dried (SSD) weight of samples at 7th day after casting in gram.

It can be seen that “*Mass loss*” index results showed in Figure 4.35 (b) followed the same trend as drying shrinkage presented in Figure 4.35 (a) over the 56 days of testing period. Moreover, the results demonstrated in Figure 4.36 indicated that except for samples prepared with 40% rubber content, all mixes complied with the requirement of RTA Specification (RTA R83 2010) which limits the drying shrinkage to 450 microstrains at 21-day drying shrinkage.

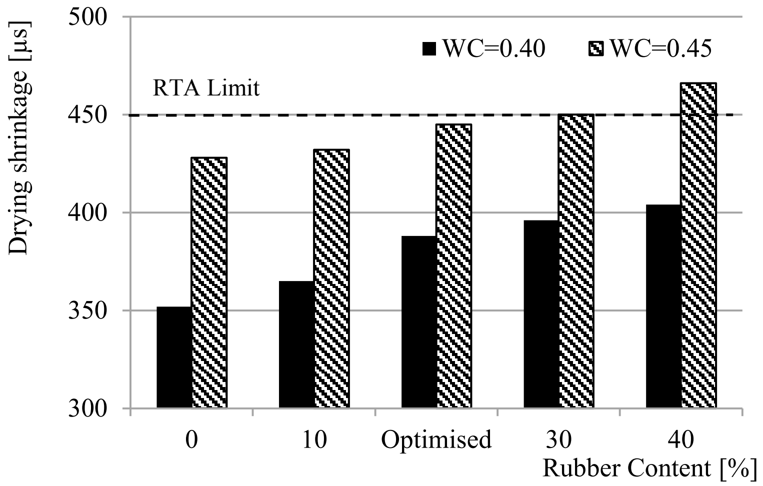


Figure 4.36: The 21 days drying shrinkage of samples with different rubber content

According to the Australian Standard AS3600, the drying shrinkage strain ε_{cs} can be determined for conventional concrete by conducting measurement after eight weeks of drying conditioning, in accordance with the Standard AS1012.13 test method or by calculation in accordance with Clause 3.1.7.2 of Standard AS3600. In addition to applying the Standard AS1012.13 test method, this study investigated the applicability of cluse 3.1.7.2 of the Australian Standard AS3600. The Australian Standard AS3600 introduces drying shrinkage model to predict the free drying shrinkage respond of rubberised concrete instead of measuring concrete shrinkage strain directly, using Standard AS1012.13. The Australian Standard AS3600 denoted that the design shrinkage strain of concrete ε_{cs} should be calculated as the sum of the chemical (autogenous) shrinkage strain ε_{cse} and the drying shrinkage strain ε_{csd}.

$$\varepsilon_{cs} = \varepsilon_{cse} + \varepsilon_{csd} \tag{4.12}$$

where, ε_{cs} is design shrinkage, ε_{cse} autogenous shrinkage is and ε_{csd} is drying shrinkage strain. The autogenous shrinkage strain shall be taken as

$$\varepsilon_{cse} = \varepsilon^*_{cse} \times \left(1 - e^{-0.1 \times t}\right) = \left(0.06 f'_c - 1\right) \times \left(1 - e^{-0.1 \times t}\right) \times 50 \times 10^{-6} \tag{4.13}$$

where, t is time in days after the setting of concrete, ε^*_{cse} is final autogenous shrinkage, and f'_c is the 28-day characteristic compressive strength of concrete in MPa.

At any time t after the commencement of drying, the drying shrinkage strain shall be taken as:

$$\varepsilon_{csd} = \frac{\left(0.8 + 1.2e^{-0.005t_h}\right) \times t^{0.8}}{t^{0.8} + 0.15t_h} \times k_4 \times \left(1 - 0.008 \times f_c'\right) \times \varepsilon^*_{csd.b} \tag{4.14}$$

where, t is the time after the commencement of drying in days, k_4 is selected 0.6 based on the ambient condition that drying shrinkage occurring, f_c' is the 28-day characteristic compressive strength of concrete in MPa, t_h is hypothetical thickness of a member in mm shown in Equation (4.15) and $\varepsilon^*_{csd.b}$ is the final basic drying shrinkage strain, which is 800×10^{-6} for Sydney.

$$t_h = \frac{2A_g}{u_e} \tag{4.15}$$

where, A_g gross cross-sectional area of a member in mm² and u_e exposed perimeter of a member cross-section plus half the perimeter of any closed voids contained therein in millimeters

Consideration shall be given to the fact that ε_{cs} provided by Clause 3.1.7.2 of the Standard AS3600 has a range of ±30% error. The calculated drying shrinkage results, based on the Standard AS3600 model, compared with the real test results, measured according to drying shrinkage test AS1012.13, as shown in Table 4.17.

Table 4.17: Experimental drying shrinkage results (AS1012.13) up to 56 day vs. the prediction of numerical model (AS3600)

Mix ID	Rubber content [%]	7-day results		14-day results		28-day results		56-day results	
		AS1012.13 [µs]	AS3600 [µs]	AS1012.13 [µs]	AS3600 [µs]	AS1012.13 [µs]	AS3600 [µs]	AS1012.13 [µs]	AS3600 [µs]
0.40/00CR	00	223	305±92	332	384±115	373	453±136	496	502±151
0.40/25CR	25	246	326±98	370	419±126	407	502±151	514	565±170
0.40/40CR	40	258	337±101	385	436±131	423	526±158	538	596±179
0.45/00CR	00	245	310±93	393	392±118	464	464±139	554	516±155
0.45/20CR	20	258	327±98	411	420±126	480	504±151	558	567±170
0.45/40CR	40	255	341±102	427	443±133	506	535±160	591	607±182

It can be seen that introducing rubber did not reduce the validity of the model introduced by the Standard AS3600 and the experimental drying shrinkage results for rubberised concrete were aligned with the numbers calculated from the Standard AS3600 drying shrinkage model.

Chapter 5

Conclusions

5.1 Conclusions

This research is intended to provide information that can ultimately be used for preparing rubberised concrete for rigid pavement applications. This study was carried out to assess crumb rubber concrete properties in which the crumb rubber particles were treated based on the water-soaking method. In addition, the best method of treating rubber with sodium hydroxide solution was studied. Moreover, the mechanical and shrinkage performance of rubberised concrete was studied in-depth. Referring to the results achieved for water soaking method, the following concluding remarks can be drawn:

- The performance of different pre-treatment methods of crumb rubber were examined and evaluated. The "water-soaking method" was selected as the best treating method because of its advantages revealed according to the achieved results in this study. The benefits of this method can be listed as (i) it is an inexpensive and practical procedure; (ii) it can make homogenous and evenly distributed rubber particles in the concrete mix with a lower entrapped air, and (iii) it improves the formation of the bond between rubber particles and the cement paste.

- This study clearly highlighted that the mix design should be based on aggregates volume if any replacement of aggregates with rubber is required. Rubber substitution considering weight of aggregates may end up with an incorrect mix proportion, which is not adjusted for one cubic metre of concrete.

- The proper water to cement (WC) ratio was meticulously studied. The results of trial mixes indicated that a rubberised mix prepared with water-cement ratio of 0.35 requires a high dosage of water reducer (WR) to achieve the target workability. It was revealed that addition of too much WR caused segregation in the mix and reduction of mix cohesiveness. In contrast, it was observed that mixing rubber into a mix series, containing high WC ratios (i.e. 0.50 and 0.55) was not applicable either. Those mixes were highly sensitive to the application of external forces or rodding, and it was very difficult to compact them without rubber segregation. According to the results, the applied WC for rubberised concrete can be between 0.4 and 0.45.

- The high concentrations of rubber particles, such as mixes prepared with 50% to 70% rubber were investigated. It was revealed that the high rubber concentration resulted in a non-homogenous mix, and formation of the weak rubber to rubber connections in the mix, leading to accelerate crack propagation and early failure of the mix.

- The test results of rubberised concrete contained water-soaked rubber were compared to the test results of a rubberised concrete type with untreated rubber. Using the water-soaking treatment method, the prepared rubberised concrete had a relatively less strength reduction. It was observed that the improvement was more significant for compressive strength rather than flexural strength. Samples prepared by water-soaking treatment rubber had 22% and 8% higher compressive and flexural strengths, respectively, compared to untreated rubber.

- The fresh property tests results revealed that rubber content up to 40% resulted in an increase in AC up to 6.1% and a decrease in MPV down to 2142 kg/m^3. Although slump number was decreased by the increase of rubber content, slump number was adjusted to the target value of 60 mm by addition WR to mixes. The hardened property test results indicated that replacing up to 40% of sand volume with rubber strength of samples continuously were declined. It can be noted that, for each 10% (≈30 kg/m^3) replacement of sand with rubber, the compressive and flexural strengths reduced 17% and 8%, respectively. In addition, results revealed that the ratio of flexural/compressive strength (f_{ctm}/f_{cm}) was enhanced significantly by increasing rubber content.

- The failure patterns for the compressive samples were studied carefully. Unlike the plain concrete, it was found that there was no major crack being responsible for the sample failure. On the contrary, a number of cracks together resulted in failure of rubberised samples. However, rubberised concrete samples could hold themselves even after failure without shattering to pieces. For both flexural and compressive tests, rubberised samples did not present a sudden intense cracking under the maximum loads. Samples had a gradual failure with slow propagation of crack until the failure occurred.

- The findings indicated that the ratio of flexural/compressive strength (f_{ctm}/f_{cm}) was enhanced significantly by increasing rubber content. Moreover, results revealed a significant improvement in the flexural strain capacity of the produced rubberised concrete. The higher flexural strength and lower elastic modulus was observed for modified concrete with a water-soaked treated type of rubber compared to the same strength concrete without adding rubber.

- A developed model for approximation strength of rubberised concrete was introduced. Strength of concrete at different ages can be approximated based on the volume fraction of rubber content and water-cement ratio of mixes. Using the model, the strength of concrete samples at different testing ages could be approximated by error of 5%, when it was verified with the experimental test data.

- Modification of concrete with crumb rubber had a positive effect on fatigue behaviour of concrete pavement. Although, introducing rubber at a low content had a negative effect on fatigue, introducing 20% or more rubber enhanced the resistance of samples against the fatigue resulted from the cyclic loads.

Referring to the results of investigation on the optimum duration for treatment of crumb rubber with the alkali solution in order to maximise the crumb rubber concrete strength, following conclusions are made:

- Results revealed that the concrete strength was reduced in both rubberised concrete with or without treatment. However, using the optimised sodium hydroxide treatment method, the prepared rubberised concrete had a relatively less strength reduction. It was observed that the improvement was more significant for compressive strength rather than flexural strength. Compared to untreated rubber, samples prepared by optimised sodium hydroxide treatment rubber had 25% and 5% higher compressive and flexural strengths, respectively.

- SEM images of rubber particles indicate that when sodium hydroxide treatment was extended from 20 minutes to 7 days, the surfaces of the rubber particles became rougher. Fresh and hardened test results of the rubberised concrete, however, revealed that the rougher surface of the crumb rubber particles did not lead to better adhesion characteristics of the rubberised concrete for all treatment methods used. According to results achieved from the inspection of SEM images, three periods of treatments involved 20 minutes, 24 hours and 7 days were examined. Experimental results revealed that the sodium hydroxide treatment had the optimum duration of 24 hours. Applying treatment for 20 minutes duration was found not to be sufficient. Similarly, a longer treatment duration of 1 week also proved the deficiency of the treatment.

- The required treatment duration may vary based on the extent of rubber surface dirtiness, source tyres constituents' properties and concentration of the alkali solution. It is highly recommended for any attempt regarding the use of treated crumb rubber in concrete, trial mix series be prepared with the three suggested periods of 20 minutes, 24 hours and 7 days. Thereafter, the decision regarding the optimum duration of treating rubber with sodium hydroxide can be made based on the result of trialled periods.

This research covered the effects of using recycled crumb rubber on shrinkage properties of concrete. The following conclusions can be drawn from the results:

- It was observed that adding more rubber into the mix series, decreases concrete bleeding index significantly. In addition, test results indicated that introducing 30% or more rubber into concrete results in difficulty with finishing of pavement surface and should be avoided.

- Although, adding rubber reduces the maximum load that samples can resist in fracture tests, the total area under the load-deflection curve increases slightly by the increase of the rubber content. However, the observed enhancement in the toughness index was not found significant.

- Plastic shrinkage test results revealed that the average crack widths, lengths and areas reduced significantly by adding 20%-25% rubber into the mix series. It was observed that by introducing the optimised content of rubber to concrete mix series, the crack reducing ratio (*CRR*) index was improved notably. Moreover, the time of the first crack occurring was delayed significantly. However, adding extra rubber to mix series eliminated all these improvements and showed an inverse impact on the plastic shrinkage properties of the rubberised concrete slabs.

- It was found that adding rubber into concrete resulted in higher free drying shrinkage strain. In addition, drying shrinkage test results revealed that the AS3600 numerical model for prediction of the concrete design shrinkage remains valid to be applied for the rubberised concrete.

Accordingly, by considering the results of fresh property tests, hardened property tests, and shrinkage tests, it could be concluded that rubberised concrete prepared with the rubber content in the range of 20% to 25% had the most promising properties and could comply with the requirements of the Australian concrete pavement specifications.

5.2 Recommendations for Future Investigations

In this research significant strides have been made to elaborate the best procedure of preparing and treating crumb rubber, mixing rubber into a concrete mix and conducting tests on rubberised concrete sample. Several aspects of rubberised concrete suitable for rigid pavement construction still need further investigation. The main areas considered for future studies are listed as follows:

a) The rubber type investigated in this research was crumb rubber size, which is classified as a fine rubber size. Introduction coarse size (>4.75 mm) of recycled waste tyre rubber is suggested for future research. This research only considered the conventional concrete pavement named base layer in Australia, with 28-day characteristic compressive strength of 32 MPa. A future suggested research can assess the application of coarse size rubber for preparing lean mix concrete. Lean mix is the most common form of bound subbase used in practice, which is placed as mass concrete under the base layer pavement. Introduction of rubber in a larger size can have higher negative impact on decreasing of concrete strength. The strength for lean mix should satisfy 28-day compressive strength of about 15 MPa according to the Australian specification (Austroad 2009). This research investigated the effect of introducing crumb rubber in the volume of up 70% fine aggregate. It was concluded that rubber content between 20% and 25% of the fine aggregate volume can be a suitable content, which can satisfy the Australian specifications. However, considering the lower requirement for strength of lean mix, for the coarse size of rubber, it is highly recommended to trial a wider range up to 100% of the coarse aggregate volume.

b) This investigation assessed the effects of “rubber soaking method” on fine size of rubber named crumb rubber. It was revealed that this method had very positive effects to mitigate the strength drawbacks in preparation of rubberised concrete. Accordingly, it is highly recommended applying the introduced method of rubber soaking on coarse size of rubber, in order to assess the effectiveness of this method.

c) A limited addition of fly ash is allowed in pavement concrete mix. Adding fly ash is conducted for compensating aggregate grading deficiencies, reducing concrete shrinkage and improving workability and durability of concrete.

Moreover, it offsets the usage of cement, and hence reduces the costs as cement is the most expensive component in pavement concrete. Accordingly, considering the provided information by this study, for any future research, mixing fly ash with the cement is strongly suggested. The result of utilising fly ash in cementitious material can be compared with the current results to make a wider framework of understanding of introducing rubber into the concrete mix.

d) Considering the 3-day up to 56-day compressive strength test results, it was found that rubberised concrete gained lower strength by passing the time. Hence, it is recommended to conduct a series of compressive strength test over the long-term duration of 56 to 1000 days in any future study. It should be performed in order to quantify any larger than the expected negative effect of rubber on concrete over the long run.

e) This study covered the drying shrinkage results for rubberised concrete up to 56 days. It is recommended to conduct a series of drying shrinkage tests over a long-term duration of 56 to 1000 days in any future study.

f) More specific pavement tests such as permeability, surface abrasion and durability test are required to be conducted in the future studies.

g) The higher shrinkage observed for rubberised concrete need to studied more in future research to evaluate if the higher shrinkage translates to a future cracking risk. It would be topic of a future study to check the combined effects of higher shrinkage, while restrained, and the improved tensile strain capacity of the crumb rubber concrete

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