STRESS-STRAIN RESPONSE OF FULL SCALE RUBBERIZED REINFORCED CONCRETE COLUMN UNDER VERTICAL LOAD

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By

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I hereby declare that all corrections and comments made by the supervisor(s) and examiner have been taken into consideration and rectified accordingly.

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ABSTRAK

Kajian ini menyiasat tingkah laku tiang konkrit bergetah bertetulang berskala penuh dengan menggantikan getah carikan bersama agregat halus. Kajian ini bertujuan untuk mengkaji tindak balas struktur dan keupayaan menanggung beban tiang tetulang konkrit tertakluk kepada beban menegak. Kajian ini menumpu kepada keupayaan struktur tiang konkrit pendek yang mengandungi getah carikan. Sebahagian daripada agregat halus digantikan dengan getah carikan yang berukuran antara 0.05 mm hingga 5 mm berdasarkan isipadu. Ujian mampatan dijalankan untuk memperoleh prestasi struktur tiang konkrit bergetah bertetulang pada hari ke 28. Tiang konkrit dikenakan beban yang disematkan dikedua-dua hujung tiang tanpa kesipian. Kekuatan mampatan, mod kegagalan tiang, modulus elastik dan kemuluran tiang konkrit bergetah bertetulang direkodkan dan dianalisis. Keputusan menunjukkan bahawa penggantian 15% getah carikan daripada agregat halus mengurangkan kekuatan konkrit disebabkan oleh pengurangan dalam ketumpatan. Tiang konkrit bergetah bertetulang menunjukkan prestasi yang lebih baik dari segi kemuluran berbanding tiang konkrit bertetulang biasa.

ABSTRACT

This study investigates the behaviour of full scale rubberized reinforced concrete column designed by replacing crumb rubber with fines aggregate. The aim of this study is to investigate the structural response and load carrying capacity of rubberized concrete column subjected to vertical load. This study focuses on the structural performance of short concrete column containing crumb rubber. Fine aggregates were partially replaced by crumb rubber with the size between 0.05 mm to 5 mm by volume. The compression test was carried out to obtain the structural performances of rubberized concrete column at the age of 28 days. The columns were loaded as pinned-end column at both end with no eccentricity. The compressive strength, failure mode of column, elastic modulus and ductility of rubberized concrete column were recorded and analysed. The result shows that the replacement of 15% crumb rubber in fine aggregate reduces the strength of the concrete due to the reduction in concrete density. The rubberized concrete column showed better performance in ductility than normal concrete column.

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CHAPTER 1

INTRODUCTION

1.1 Background

One of the largest and most problematic sources of waste products in Malaysia is scrap tires due to huge amount of discarded tires every year. A study done by Thiruvangodan (2006) shows that, there is steady increase in the motorcar waste tire generated annually in Malaysia. The number of motorcar waste tires generated annually in the country was estimated to be 8.2 million or approximately 57,391 tonnes. About 60% of the waste tires are disposed via unknown routes. It is unknown to what extend these tires are disposed off in an environmental friendly and legal way.

Generally, the cheapest and easiest way to decompose used tires is by burning them. However, in some country this method is prohibited by law. Recycling of the used tires are the best way to reduce the amount of scrap tires in the landfill. Many experimental investigations were done to find out the practicality of using scrap tires as a construction material. The most common use of scrap tires has been in highway asphalt mixes. However, in recent years the mixes of rubber particles in Portland cement has gained more interests. To prove that the recycled tires can be used in concrete, many experimental investigation of scrap tire as a replacing of crumb rubber for coarse and fine aggregates has been done.

Using crumb rubber as replacing aggregate in concrete mix would be able to provide an efficient way of utilizing rubber. According to Youssf et al., (2015), crumb rubber concrete (CRC) in column structure increased the hysteretic damping ratio and energy dissipation by 13% and 150% respectively. In addition, CRC column was able to sustain a lateral load of about 98.6% of the load sustained by the conventional column, even though its compressive strength was 28% lower. This indicates that rubber can be used in concrete columns with no significant effect on their lateral strength and deformability even though it has lower axial compressive strength. A research study by Khatib and Bayomy (1999) and Scimizze et al., (1994) suggested that rubber content should not exceed 17%-20% of the total aggregate volume to maintain reasonable structural performance.

Although, in many research concluded that rubber has significantly decreased the overall strength of concrete, previous research indicates that rubberized concrete has improved energy absorption and ductility compared to conventional concrete. A research conducted by Zheng et al., (2008) concluded that the use of rubber with a rubber content of 15% is more efficient in getting lower brittleness index. Rubberized concrete has lower brittleness index than normal concrete, signified that rubberized concrete had a higher ductility performance and a good energy absorption than the normal concrete.

1.2 Problem statement

The work on rubberized concrete has shown that the existence of rubber in the concrete may reduce drying shrinkage, brittleness, and elastic modulus, which might also improve the overall durability and serviceability of concrete. Most of the previous findings have shown that rubber concrete would suffer a reduction in compressive strength while it may increase ductility. In addition, structural responses of rubberized concrete subjected to a full scale axial load is still not known. Further investigation needs to be carry out to explore more about the use of rubber in replacement of fine aggregate in concrete column structure. Besides, more research needs to be carry out to investigate the load carrying capacity of rubberized concrete under vertical load. Thus, more research is required to evaluate the stress-strain response of full scale rubberized reinforced concrete column.

1.3 Objectives

The objectives of this study are as follows:

1. To investigate the structural response of rubberized concrete subjected to a full scale axial load.
2. To investigate load carrying capacity of rubberized concrete column subjected to pinned end condition.

1.4 Scope of work

This study mainly focuses on the effect of crumb rubber on the structural performance of RC short column. All columns comprise of six similar square RC short columns with dimension of 150 mm x 150 mm x 500 mm which are three rubberized concrete columns and three normal concrete columns. The rubberized concrete columns will be using 15% of crumb rubber as replacement for fine aggregate by unit volume. Meanwhile, the normal concrete was used as the control concrete. All 6 tested columns were loaded as pinned-end columns at both ends with no eccentricity. The specified target strength for normal concrete column is 25 N/mm^2 at 28 days. Laboratory work such as sieve analysis, concrete mix design, trial mix, compressive strength test and axial load test were carried out to study the structural performances of rubberized concrete column. The results obtained were then analysed and compared with the normal concrete.

1.5 Dissertation outline

1.5.1 Chapter 1: Introduction

The introduction describes the research problem or question and lays out the theoretical argument behind it. It justifies the need of information to develop theory and understanding about the study. Introduction in this dissertation comprises the background, problem statement, objective and scope of work.

1.5.2 Chapter 2: Literature review

This chapter reviews what has already been written in the fields on the topic of the study. It review the theory that are relevant to research questions.

1.5.3 Chapter 3: Methodology

This chapter explains the methodology of this study. Sections in this chapter includes experimental work and procedure to be used for the laboratory work.

1.5.4 Chapter 4: Results and discussion

This chapter presents the results of the analyses and the discussion of the results obtained.

1.5.5 Chapter 5: Conclusions and recommendations

This chapter provides the research conclusions and recommendations from the results and discussion.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

There is a steady increase in the waste tire generated annually in Malaysia. Currently there is no specific law or regulation which oversee waste tire management. Tire dealers face substantial pressure when the waste tires increases in their premise and often resulting in improper storage of the wastes. They do not have any guidance or assistance from their dealers or authorities for proper management and disposal of waste tires (Thiruvangodan, 2006)

Scrap tires are being generated and piled up in large volumes causing an increasing hazard to the environment. In order to eradicate the negative effects of these depositions and in terms of sustainable development there is immense interest in the recycling of these non-hazardous solid wastes. The potential of using rubber from tattered tires in many civil engineering works has been studied for more than 30 years. Applications where tires can be used and where the addition of tire rubber has proven to be effective in protecting the environment and preserving natural resources include in the production of cement mixtures.

Shredded tires also known as crumb rubber has been identified by researchers as the applicable materials to be used in replacing natural aggregate in concrete mixtures. Numerous research regarding the use of crumb rubber as a replacement of aggregate has been studied and these rubber particles could contribute to a new type of concrete with unique mechanical and fracture characteristics. Table 2.1 show the overview from previous research.

Table 2.1 Reviews from previous research

Researcher	Year	Title	Related Parameter of Study	Nature of Work	Conclusion
Eldin and Senouci	1994	Rubber-tire particles as concrete aggregate	Strength and toughness properties of concrete	Experimental	The rubberized concrete mixture exhibits lower compressive and splitting-tensile strength than the normal concrete. Rubberized concrete did not demonstrate brittle failure, but had a ductile, plastic failure and had the ability to absorb a large amount of plastic energy under compressive and tensile loads.
Khatib and Bayomy	1999	Rubberized Portland Cement Concrete	Properties of fresh concrete, compressive strength, and flexural strength	Experimental	Rubberized PCC mixtures can be made using ground tire rubber in partial replacement by volume of normal fine or coarse aggregates. Rubber contents should not exceed 20% of the total aggregate volume due to the reduction in strength as the presence of high rubber content.
Khaloo et al.,	2008	Mechanical properties of concrete containing a high volume of tire-rubber particles	Properties of fresh concrete and hardened concrete properties	Experimental	Workability of rubberized concrete with coarse rubber particles is reduced with increasing rubber concentration, however, rubberized concrete with fine rubber particles exhibits an acceptable workability with respect to plain concrete. Due to the decrease in ultimate strength and the tangential modulus of elasticity, rubber concentration should not exceed 25%.

Researcher	Year	Title	Related Parameter of Study	Nature of Work	Conclusion
Zheng et al.,	2008	Strength, modulus of elasticity, and brittleness index of rubberized concrete	Compressive strength, static and dynamic modulus of elasticity, and brittleness index of rubberized concrete.	Experimental	Compressive strength and modulus elasticity of rubberized concrete decreased with the increasing amount of rubber content. Rubberized concrete had higher ductility performance than the normal concrete.
Taha et al.,	2009	Mechanical, fracture, and microstructural investigations of rubber concrete	Properties of fresh concrete, compressive strength, mechanical and fracture properties, and microstructural feature.	Experimental	The use of rubber particles as aggregate in concrete enhanced energy absorption and fracture criteria compared with normal concrete. Microstructural investigation of the rubber concrete supported the view that the major reduction of strength might be attributed to the behaviour of the tire particles as a soft aggregates rather than the reduction of bond between the tire particles and cement paste.
Aiello and Leuzzi	2010	Waste tyre rubberized concrete: properties at fresh and hardened state	Workability, unit weight, compressive and flexural strength and post-cracking behaviour.	Experimental	The rubberized concrete mixtures has lower unit weight compared to plain concrete and good workability. The results of compressive and flexural tests indicated a larger reduction of mechanical properties of rubcrete when replacing coarse aggregate than fine aggregate. The post-cracking behaviour of rubberized concrete showed a good energy absorption and ductility indexes by adding coarse rubber chips in place of coarse aggregate.

Researcher	Year	Title	Related Parameter of Study	Nature of Work	Conclusion
Pacheco-Torgal et al.,	2012	Properties and durability of concrete containing polymeric wastes (tyre rubber and polyethylene terephthalate bottles): An overview	Fresh concrete properties and hardened concrete properties	Experimental	Tyre waste concrete is specially recommended for concrete structures located in areas of severe earthquake risk. It also can be used for non-load-bearing purposes such as noise reduction barriers.
Issa and Salem	2013	Utilization of recycled crumb rubber as fine aggregates in concrete mix design	Compressive strength, ductility, insulation properties, and damping properties	Experimental	Good compressive strength results were recorded at rubber contents lower than 25% in replacement of crushed sand. Rubber enhanced ductility of concrete, insulation properties, and damping properties.
Bing et al.,	2014	Experimental research on properties of fresh and hardened rubberized concrete	Properties of fresh and hardened rubberized concrete	Experimental	An increase in rubber content leads to a decrease in slump and an increase in air content because of the rough surface of rubber. An increase in rubber content decreases compressive strength, elastic modulus, and flexural strength because of its lower stiffness and poorer bonding between rubber and the paste matrix.

Researcher	Year	Title	Related Parameter of Study	Nature of Work	Conclusion
Guo et al.,	2014	Compressive behaviour of concrete structures incorporating recycled concrete aggregates, rubber crumb and reinforced with steel fiber, subjected to elevated temperatures.	Compressive strength, Young's modulus, and energy absorption	Experimental	The results showed that both the compressive strength and stiffness of concrete mixes decreased after exposure to elevated temperature with higher replacement of fine aggregate by rubber leading to lower compressive strength and stiffness magnitude. Furthermore, rubber crumbs significantly enhanced the energy absorption capacity and explosive spalling resistance.
Naito et al.,	2014	Assessment of crumb rubber concrete for flexural structural members	Mechanical properties of crumb rubber concrete (CRC), and flexural resistance for structural application	Experimental	The additional of crumb rubber results in decrease in unit weigh, compression strength, splitting tensile strength, and elastic modulus. The modulus of rupture was not sensitive to replacement of up to 40% rubber aggregate and flexural failure modes occur at lower demand levels due to the use of rubber replacement.
Youssf et al.,	2015	Experimental investigation of crumb rubber concrete columns under seismic loading	Ductility, damping ratio, and energy dissipation.	Experimental	The results indicated that the use of CRC increased the hysteretic damping ratio and energy dissipation of the columns. However, the viscous damping ratio of CRC decreases compared to conventional concrete column. The CRC column was able to sustain a lateral load and ultimate drift of about 98.6% and 91.5% respectively, of those sustained by the conventional column.

Researcher	Year	Title	Related Parameter of Study	Nature of Work	Conclusion
Zhang and Zhao	2015	Internal stress development and fatigue performance of normal and crumb rubber concrete	Early age internal stress evolvement of CRC and fatigue behavior.	Experimental	Results show that the internal stress that developed in restrained rubber included concrete was lower than that in ordinary cement concrete. The stress relaxation effect due to the low elastic modulus of rubber. Crumb rubber concrete possessed much longer fatigue life than ordinary concrete at room temperature, however, at 70℃, the fatigue life of both ordinary concrete or crumb rubber concrete is much lower than either concrete at normal temperature.
Aslani	2016	Mechanical properties of waste tire rubber concrete	Compressive strength, tensile strength, flexural strength, modulus of elasticity, strain at maximum strength, and compressive stress-strain curve of RC	Experimental	The compressive strength decreased perceived in the RC with increasing rubber content because the cracks are started rapidly near the rubber particles as the rubber particles are much softer than cement paste, and rubber particles function as voids in the concrete matrix because of the absence of adhesion between the rubber particles and the paste. Results show that the decrease in the tensile strength with rubber was lower than that in the compressive strength. Flexural strength decrease with the increase of the rubber content.
Ismail and Hassan	2017	Ductility and cracking behaviour of reinforced self-consolidating rubberized concrete beams	Curvature ductility, ultimate flexural strength, and cracking characteristic	Experimental	The results indicated that although the flexural capacity of the tested beams decreased with the addition of crumb rubber, adding crumb rubber improved the beams' curvature ductility and reduced its self-weight. Adding crumb rubber also limit the flexural crack widths but with a slightly higher number of cracks compared to beams without crumb rubber.

2.2 Crumb rubber

Crumb rubber is a material produced by shredding used tires. Materials characterization experiments have been conducted to determine the practicality of using crumb rubber in Portland cement concrete. The properties of fresh concrete containing crumb rubber show reduction in workability as signified by the reduction in slump values at the higher rubber volumes increased the air contents and decreased the unit weights as shown in Figure 2.1 (Khatib and Bayomy, 1999).

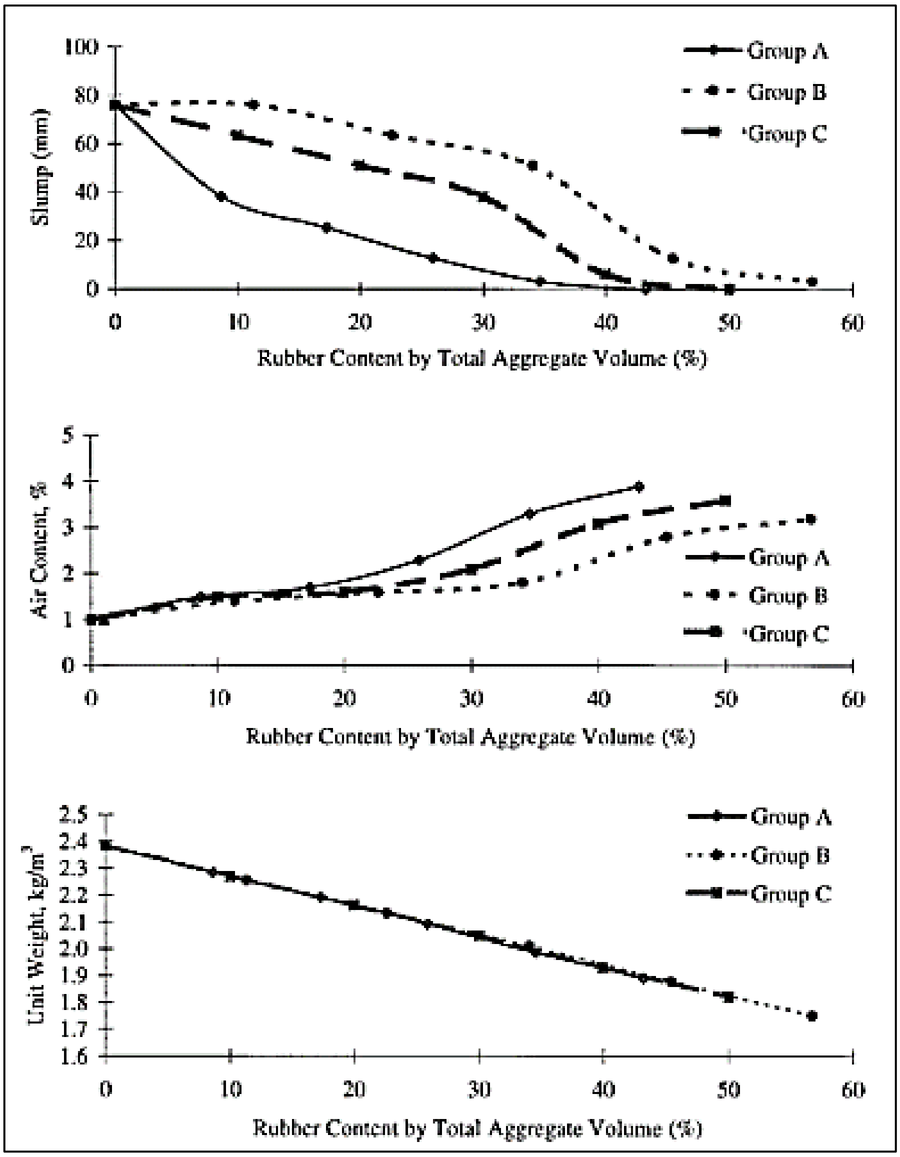

Figure 2.1 Effect of rubber content on properties of fresh rubberized Portland cement concrete mixture (Khatib and Bayomy, 1999)

Research has shown that replacement of conventional aggregate with rubber resulted in decrease in compressive and tensile strength. Eldin and Senouci (1994) conducted experiments to examine the strength and toughness properties of rubberized concrete mixtures. Their results indicate that there is about an 85% reduction in compressive strength while the tensile strength reduced by about 50% when the coarse aggregate was fully replaced by rubber. A smaller reduction in compressive strength, about 65% was observed when sand was fully replaced by fine crumb rubber. Concrete containing rubber did not undergo brittle failure under compression or split tension, and it increases fracture toughness. Khatib and Bayomy (1999) observed similar behaviour and recommended a practical limit of 20% volumetric replacement of aggregate to maintain reasonable structural performance.

Microstructural investigation of the rubber concrete by Reda Taha et al., (2009) views that the major reduction of strength might be attributed to the behaviour of the tire rubber particles as soft aggregate rather than to the reduction of bond between the tire particles and cement paste. Further research on microstructure of crumb rubber indicated that tire chips increased the fracture toughness and impact resistance of the concrete. Figure 2.2 shows the effect of increasing tire rubber particles content on the fracture toughness of rubber concrete. The increase in fracture toughness of concrete with tire rubber particles inclusion can be attributed to the ability of the tire rubber particles to add a few toughening mechanism to normal concrete. The rubber acted as an additional energy absorber that toughened the concrete.

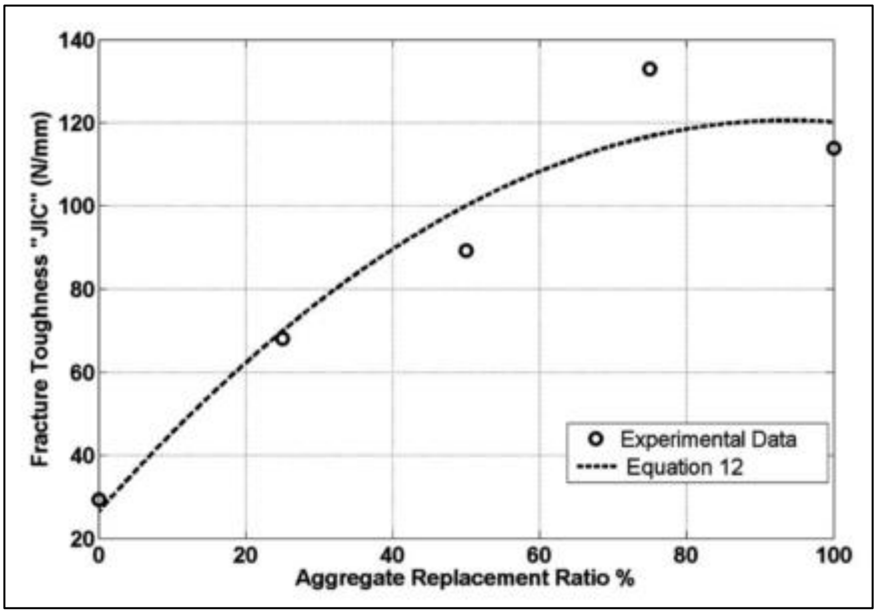

Figure 2.2 Experimental versus analytical model for predicting toughness of rubber concrete (Reda Taha et al., 2009)

Workability, fresh density, compressive strength, tensile splitting strength, flexural strength and water permeability of concrete with different rubber particle sizes were studied and compared by Su et al., (2015). They summarized that using different sizes of rubber particles in concrete as part of the fine aggregates affects the workability and water permeability more than the fresh density and concrete strengths. Furthermore, concrete specimens with larger rubber particles show a better workability than those with finer ones. Conversely, concrete with finer rubber particles has better performance in strengths and water permeability. Summary of the result from the research by Su et al., (2015) is shown in the Figure 2.3.

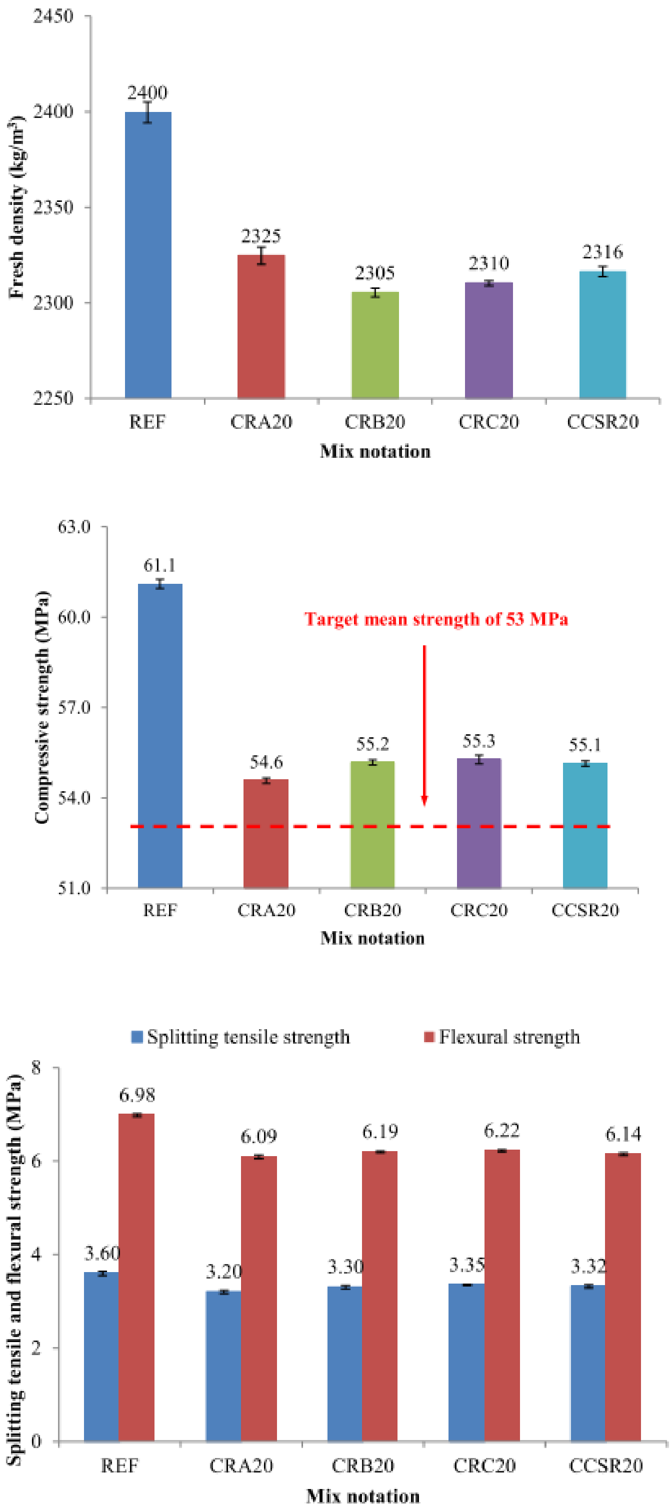

Figure 2.3 Properties of concrete with different sizes of rubber particles (Su et al., 2015)

The modulus of elasticity is one of the most important elastic properties of concrete since it impacts the serviceability and performance of concrete structure. Research done by Zheng et al., (2008) revealed that the modulus elasticity of rubberized concrete decreased with increasing amount of rubber content. For brittle materials such as concrete, which has larger elastic energy capacity than the plastic energy capacity, the brittleness index value is higher compared to other ductile materials. It is found that, an additional of rubber in concrete can reduce the brittleness index values and improve ductility of concrete, which is changing the concrete from brittle material to ductile material.

2.3 Advantages of rubberized concrete

The use of rubber particles as aggregate in concrete showed promising results in producing a new type of concrete that has enhanced energy absorption and fracture criteria compared with normal concrete. Compressive strength and modulus of elasticity of rubberized concrete decreased with the increasing amount of rubber in the concrete. The reduction in modulus of elasticity indicates higher flexibility. However, a good compressive strength was recorded at rubber contents lower than 25% as replacement of crushed sand. Besides, rubberized concrete enhanced insulation properties and also it enhanced damping properties, since rubber absorbs vibration to a large extent (Issa and Salem, 2013). In the splitting-tensile strength tests, rubberized concrete specimen showed high capability of absorbing plastic energy.

Specimens containing rubber did not exhibit brittle failure under compression due to the rubber's plastic behaviour. Brittleness index values of rubberized concrete were lower than the normal concrete which means that the rubberized concrete had higher ductility performance than normal concrete. It can be observed from the results obtained as shown in Figure 2.4 that the brittleness index values of rubberized concrete were lower than that of normal concrete. The use of rubber content of 15% is more efficient in getting a lower brittleness index (Zheng et al., 2008).

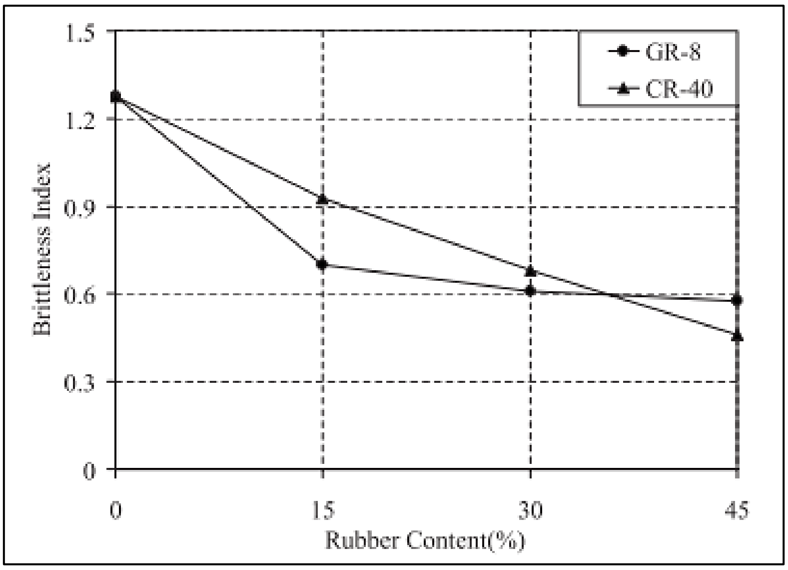

Figure 2.4 Relationship between brittleness index and rubber content (Zheng et al., 2008)

2.4 Disadvantages of rubberized concrete

Rubberized concrete mix may be suitable for non-structural proposes such as lightweight concrete walls, building facades, and architectural units. This is due to the strength of concrete which showed large reductions in strength as the rubber content increases (Issa and Salem, 2013). Figure 2.5 shows that compressive strength reduces as the rubber content increases.

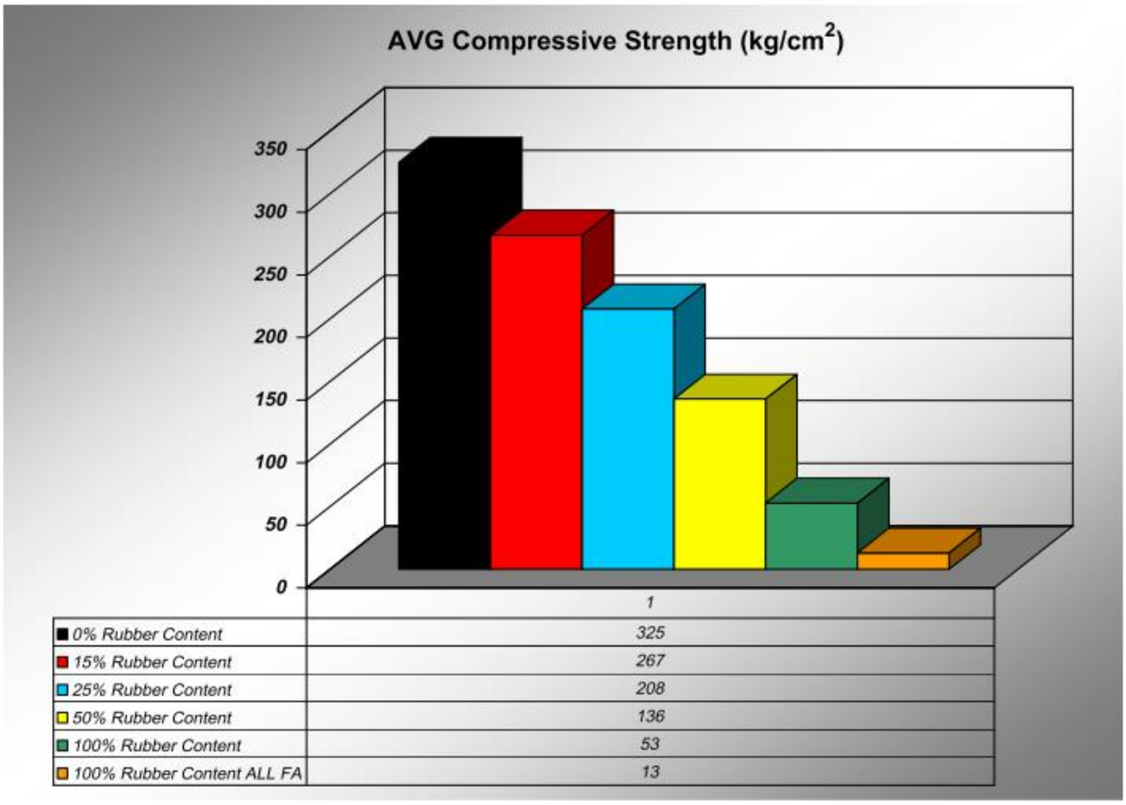

Figure 2.5 Bar chart of compressive strength versus percentage of rubber content (Issa and Salem, 2013)

Fully replacing coarse aggregate or fine aggregate with rubber is not appropriate because the loss of strength is too severe. The dynamic modulus of elasticity of rubberized concrete was lower than the plain concrete. The crushed rubber concrete introduced more reduction on dynamic modulus of elasticity of rubberized concrete than ground rubber concrete (Zheng et al., 2008).

Replacing natural river sand with relatively soft rubber aggregate is expected to reduce the concrete compressive strength. The compressive strength of the concrete increased modestly with a decrease in the rubber particle size due to a finer rubber particles have a better voids-filling ability, resulting in low void space and leading to higher compressive strength (Su et al., 2015). This can be attributed to the low stiffness and poor surface texture of the rubber particles that resulted in an inconsistency of the concrete mix, and the lack of bonding between the rubber particles and the cement paste (Eldin and Senouci, 1993).

2.5 Summary

All of the research related to replacing crumb rubber as aggregates in concrete mixes mostly show negative conclusion. Replacing aggregates with relatively soft particles such as rubber has reduced the strength of the concrete. The reduction in strength of the concrete is mostly due to the lack bonding of rubber particles and the cement paste, resulting in increasing voids in the concrete and leading to reduction in the density of the concrete. However, it was mostly agreed that the use of rubber particles as aggregates will enhance the energy absorption. Rubberized concrete specimen showed high capability of absorbing plastic energy in splitting-tensile test. However, a good result on rubberized concrete only can be achieved if the rubber content in the concrete is lower than 25% as replacement of crushed sand. Khatib and Bayomy (1999) observed similar behaviour and recommended a practical limit of 20% volumetric replacement of aggregate to maintain reasonable structural performance.

From the literature survey, it seems that almost all the previous research works related to crumb rubber concrete were limited to experimental studies or qualitative explanations of flexural members. Very little work has been done on compression member containing rubber particles, especially short column. Short columns are designed as structural members having a high stiffness with low ductility and governed by brittle shear failures. Therefore, it is necessary to extend the understanding of rubberized concrete subjected to vertical loading such as column containing rubber.

From the earlier studies, crumb rubber has been identified by researchers as the suitable material to be used in replacing natural aggregate in concrete mixtures. These rubber particles could provide a new type of concrete with unique mechanical and fracture characteristics. However, the stress-strain response of full scale rubberized concrete subjected vertical load is still unknown. Research regarding full scale product need to be studied more extensively to know the impact of using rubber particles in construction. Thus, the usage of rubber particles in construction can help to dispose waste tires.

CHAPTER 3

METHODOLOGY

3.1 Overview

This chapter discusses the experimental work and test procedures to be used for the laboratory work to evaluate the stress-strain response of full scale rubberized RC column subjected to vertical load. The laboratory work and testing methods were carried out based on American Society for Testing and Materials (ASTM) testing procedures.

3.2 Column design

Short RC specimens were prepared and tested accordingly. There were 6 specimens of short RC columns prepared as shown in Table 3.1.

Table 3.1 Specimen detail

Type of column	No of specimen
Normal RC Column (150 mm x 150 mm x 500 mm)	3
Rubberized RC Column (150 mm x 150 mm x 500 mm)	3

Each specimen had a square cross section with dimension of 150 mm x 150 mm x 500 mm. The short columns were designed to avoid the formation of secondary moment due to the slenderness effect. Moreover, the dimensions were chosen to be adaptable with the condition and capacity of the available testing machine in the laboratory. The concrete cover was 25 mm on each side of the specimen and at top and bottom as well. The shear reinforcement provided was at the minimum reinforcement required by the design standard ($A_{s,min}$). Therefore, main reinforcement bar for the specimens was 4T12 with spacing of 100 mm and R6 reinforcement was provided as shear link at space of 200 mm between centre to centre. The short RC specimens were design according to BS 8110-1:1997. Figure 3.1 shows the details of the reinforcement.

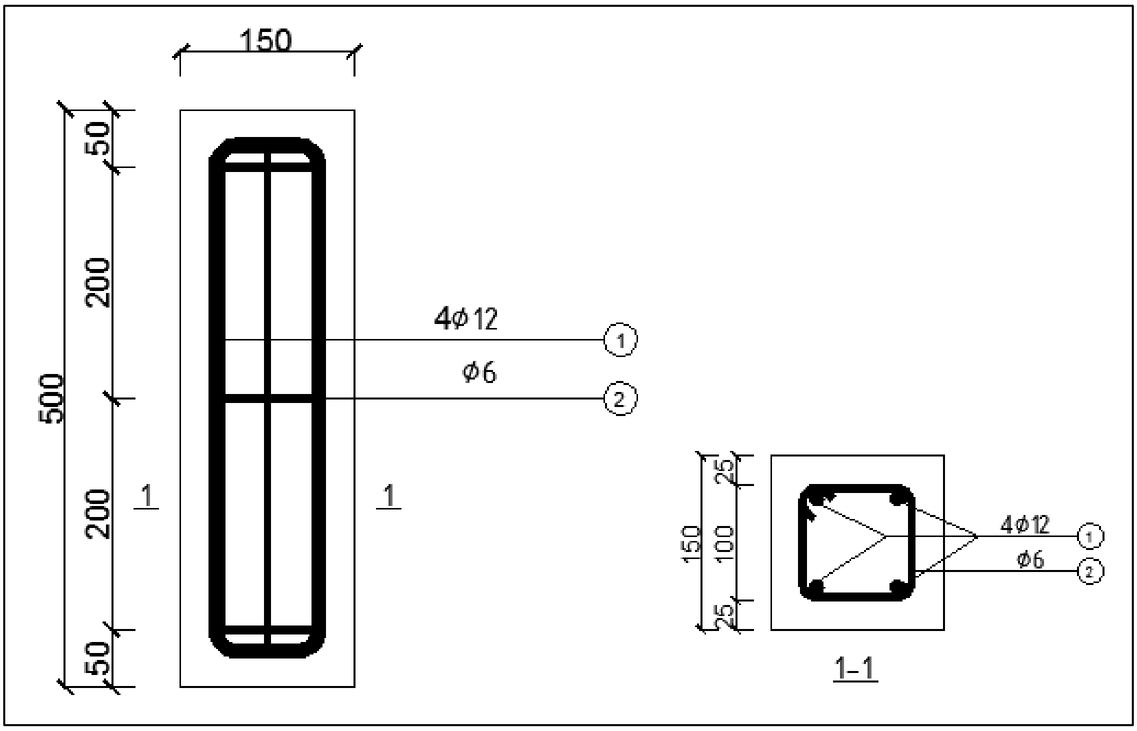

Figure 3.1 Column detail

3.3 Material preparation

The materials that have been used to produce the rubberized and normal concrete column in this research are:-

1. Ordinary Portland Cement (OPC)
2. Coarse aggregate
3. Fine aggregate
4. Crumb rubber
5. Steel reinforcement

3.3.1 Ordinary Portland cement (OPC)

Ordinary Portland cement was used in this research because it is the most common cement used in concrete construction when there is no exposure to sulphates in the soil or groundwater. The OPC which was manufactured by Tasek Corporation Berhad exceeds the quality requirements specified in the MS EN 197-1:2007.

3.3.2 Aggregate

The coarse aggregate used in this research was from crush granite rock with a maximum size of 10 mm and natural river sand was used as the fine aggregate. Sieve analysis was carried out to ensure the grading is within the requirement according to ASTM C33 (ASTM, 2016),

Figure 3.2 Coarse aggregate

Figure 3.3 Fine aggregate

3.3.3 Crumb rubber

Crumb rubbers with size between 0.05 mm to 5 mm were used in this research which were produced by mechanical shredding of tire obtained from a local recycles scrap tires factory. The density of the crumb rubber used is 570 kg/m³.

Figure 3.4 Crumb rubber

3.3.4 Steel reinforcement

The steel reinforcements used in this study were main reinforcement (high yield steel) and shear link (hot rolled mild steel). Both steels were tested according to ASTM A1034 (ASTM, 2015) to measure the strength of rebar.

3.3.5 Water

The cement used in the concrete needs water to hydrate and form Calcium-Silicate-Hydrate (C-S-H) which is the glue that holds the aggregate particles together. In this study, the water used for concrete mixing is from the tap water which is free from pollutant.

3.4 Tests for fine aggregate

This test was carried out to determine the grading of materials proposed for use as aggregates. The standard test method for sieve analysis of fine and coarse aggregate is according to ASTM C136 (ASTM, 2015).

The coarse and fine aggregates were dried to constant mass at a temperature of 110 ± 5°C. The sieves were nested in order of decreasing size of opening from top to bottom. The sample was placed on the top sieve. The sieves were then vibrated using a mechanical sieve shaker. Then, total percentages retained of the sample was calculated to the nearest 0.1% on the basis of the total mass of the initial sample. The grading of the aggregates was then determined.

3.5 Concrete mix design

The mix was designed according to the "Design of Normal Concrete Mixes" which was published by the Building Research Establishment Ltd. In 1997 (formerly by Department of Environment). The specified characteristic strength of concrete is 25 N/mm^2. The specified free-water/cement ratio is 0.5 and target specified slump test is between 10 mm – 30 mm. Maximum aggregate size used in the mixes is 10 mm. Moreover, the free-water content and cement content are 190 $kg/m^3$and 404 kg/m^3 respectively. The relative density of aggregate is 2.7 and the concrete density is 2420 kg/m^3. Furthermore, 15% of fine aggregate were replaced by crumb rubber by volume for the rubber concrete mixture. Table 3.2 shows the requirement of materials for a mix with a total volume of 0.049 m^3 per trial mix.