UNIVERSITY OF EDUCATION, WINNEBA

THE USE OF GROUND VEHICULAR TYRE AS PARTIAL REPLACEMENT FOR SAND IN CONCRETE PAVEMENT BLOCKS PRODUCTION

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(BACHELOR OF TECHNICAL EDUCATION)

A thesis in the Department of DESIGN AND TECHNOLOGY, Faculty of TECHNICAL and VOCATIONAL EDUCATION, submitted to the School of Graduate Studies, University of Education, Winneba in partial fulfilment of the requirements for award of the Master of Philosophy (Construction Technology) degree.

JULY, 2013

DECLARATION

STUDENT'S DECLARATION

I, Ohemeng Ababio Eric, declare that this thesis, with the exception of quotations and references contained in published works which have all been identified and duly acknowledged, is entirely my own original work, and it has not been submitted, either in part or whole, for another degree elsewhere.

SIGNATURE: ………………...................……………

DATE: ……………………..................……….…….

SUPERVISOR'S DECLARATION

I hereby declare that the preparation and presentation of this work was supervised in accordance with the guidelines for supervision of thesi2ss as laid down by the University of Education, Winneba.

NAME OF SUPERVISOR: Dr. Peter Paa-Kofi Yalley

SIGNATURE:…………………...................…………

DATE:………………………………........................….

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DEDICATION

This thesis is dedicated to all my family members, especially my late daughter, Emmanuelle Ohemeng Ababio.

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LIST OF ABBREVIATIONS

ASTM – American Society for Testing and Materials

BSI – British Standard Institution

C & D – Construction and demolition

CPBs – Concrete pavement blocks

CRC – Crumb rubber concrete

Cs – Compressive strength

d – Density

Fs – Flexural strength

GVT – Ground vehicular tyre

ICT – Intensive compaction tester

LH – Low heat

MOC – Magnesium oxychloride cement

OPC – Ordinary Portland cement

RCPBs – Rubberized concrete pavement blocks

RMC – Rubber modified concrete

SR – Sulphate resistant

T – Splitting tensile strength

W/C – Water cement

ABSTRACT

The use of accumulated waste materials in Ghana is still in its early phases. It will take courage for contractors and others in the construction industry to recycle selected types of waste materials for concrete products. The main objective of this research was to investigate the feasibility of using ground vehicular tyre (GVT) as a partial replacement for sand in the production of concrete pavement blocks. In this study cement, sand, quarry dust, coarse aggregate, and ground vehicular tyre were used to produce rubberized concrete pavement blocks (RCPBs). The mix proportion was 1: 1: 2: 2.25 (cement: coarse aggregate: quarry dust: sand). The GVT was used to replace sand by volume at 0%, 10%, 20%, 30%, 40%, 50% and 60%. It was observed that density, compressive strength, flexural strength, and splitting tensile strength decrease, as the GVT content increases. However, the water absorption increases, as the GVT content increases. Compressive strength level ranging from 2.48N/mm^2 to 30.20N/mm^2 was achieved when water cement ratios of 0.20 to 0.35 were used. Even though, the test results shown that the compressive strength reduces when GVT is used, the produced RCPBs can meet the minimum strength requirement of 20N/mm^2 for pedestrian walk way pavement blocks. In this work, models were also developed to predict the density and compressive strength of the produced RCPBs. It is concluded that the modified pavement blocks would contribute to the disposal of the non-biodegradable tyres, since the amount being accumulated in Ghana and the world as a whole is creating a challenge for proper disposal.

ABSTRACT

The use of accumulated waste materials in Ghana is still in its early phases. It will take courage for contractors and others in the construction industry to recycle selected types of waste materials for concrete products. The main objective of this research was to investigate the feasibility of using ground vehicular tyre (GVT) as a partial replacement for sand in the production of concrete pavement blocks. In this study cement, sand, quarry dust, coarse aggregate, and ground vehicular tyre were used to produce rubberized concrete pavement blocks (RCPBs). The mix proportion was 1: 1: 2: 2.25 (cement: coarse aggregate: quarry dust: sand). The GVT was used to replace sand by volume at 0%, 10%, 20%, 30%, 40%, 50% and 60%. It was observed that density, compressive strength, flexural strength, and splitting tensile strength decrease, as the GVT content increases. However, the water absorption increases, as the GVT content increases. Compressive strength level ranging from 2.48N/mm^2 to 30.20N/mm^2 was achieved when water cement ratios of 0.20 to 0.35 were used. Even though, the test results shown that the compressive strength reduces when GVT is used, the produced RCPBs can meet the minimum strength requirement of 20N/mm^2 for pedestrian walk way pavement blocks. In this work, models were also developed to predict the density and compressive strength of the produced RCPBs. It is concluded that the modified pavement blocks would contribute to the disposal of the non-biodegradable tyres, since the amount being accumulated in Ghana and the world as a whole is creating a challenge for proper disposal.

CHAPTER ONE

INTRODUCTION

1.1 Research Background

Cement and aggregates, which are the most important constituents used in concrete production are vital materials needed for the construction industry. This has led to a continuous and increasing demand of natural materials used for their production. Meanwhile, waste materials and by-products are being generated in vast quantities, causing detrimental effect to the world. It is therefore imperative to utilize these waste materials and by-products in construction applications. Recently, there have been successful applications of using local waste materials as a partial replacement for cement or aggregates in manufacturing concrete products in some parts of the world.

Numerous studies on applications of construction and demolition (C&D) wastes as fine and coarse aggregates material are available in the literature (Poon & Chan , 2006; Poon & Cheung, 2007), which demonstrated the possibility of utilizing huge amounts of C&D waste in concrete pavement blocks (CPBs). The use of recycled aggregates in CPBs production has been successfully implemented and is gaining wider acceptance. Karasawa, Suda, Naito, and Fujiwaran (2003) have reported that fly ash can be used as a substitute for fine aggregate in the production of CPBs. Apart from fly ash, peanut shell ash and rice husk ash can be used as partial replacement for cement in CPBs production.

Among the waste materials, pneumatic tyre is one of the most common environmental issues in the contemporary world. Each year, approximately 800 million new tyres are produced in every region of the world, in various sizes and types (Ulrich, 1998). It has also been reported that about 1 billion of used automobile tyres are generated each year globally (Vanessa, Linda, Ase, Joanne, & Krishna, 1995). Specifically, 275 million of used tyres accumulate in the United States and about 180 million in Europe (Gintautas, Audris, & Benjaminas, 2007). Waste tyre is considered as one of the common environmental issues in the contemporary world. If the tyre is burned, the toxic product from the tyre will damage the environment and thus creating air pollution. Since it is not a biodegradable material, this may affect the fertility of the soil and vegetation. Sometimes it may produce uncontrolled fire. Similarly, the other challenge to the human society is in the form of carbon dioxide emission and green house emission. These emissions are considered as highly threatening wastes to the universe (Kumaran, Mushule, & Lakshmipathy, 2008).

Existing CPB is characterized as a composite material with high compressive strength, moderate tensile strength, and with a low toughness. It is anticipated that an ideal concrete block pavement should have high tensile strength and high toughness. Therefore, minimum required strength and improved toughness of modified CPB has to be developed for trafficked pavement application. For concrete, it is found that the higher the strength, the lower the toughness (Ling, 2008). Hence it is impossible to develop high strength and high toughness concrete without modifications. Laboratory tests have shown that the addition of waste tyre rubber in concrete increase toughness, impact resistance, and plastic deformation considerably, offering a great potential for it to be used in sound barriers, retaining structures, and pavement structures (Eldin & Senouci, 1993; Goulias & Ali, 1997; Khatib & Bayomy, 1999). However, the strength of concrete containing crumb rubber is expected to be lower than those of the ordinary concrete (Toutanji, 1996; Siddique & Naik, 2004; Sukonrasukkul & Chaikaew, 2006; Ling, 2008). The reason for the strength reduction could be attributed to a reduction of quantity of the solid load carrying material and a lack of adhesion at the boundaries of the rubber aggregate, as soft rubber particles may behave as voids in the concrete matrix.

1.2 Problem Statement

In Ghana, utilization of CPBs as a paving material is wide-spread. Cement, fine aggregate, and coarse aggregate, which are the most important constituents used in manufacturing CPBs are also vital materials needed for the construction industry. This has put much pressure on the natural materials used for their production and as a result most of these natural materials are becoming scarce and expensive. A growing concern for protecting the environment and preserving natural resources by using alternative materials have been an issue in Ghana, and the world as a whole.

Statistics indicates that the total number of registered vehicles population in Ghana as at March 2012 stood at approximately 1,425,900 (Ministry of Transportation, 2012). This number of cars has led to an increase in the rate of accumulation of scrap tyres throughout the country. However, no current official data on the amount of stockpile of waste tyres are available in Ghana. Majority of such waste tyres have become mosquito breeding places and gives the worst effects when they are burnt. Even though several districts, municipals, and metropolitans are involved in waste management, they often have no clear policies on the waste management. Therefore, as a construction technologist and researcher, there is a need to seek economic and environmental friendly methods to manage these tyres in construction applications, such as concrete pavement block products.

Background information presented shows that it is possible to incorporate rubber as aggregate in concrete production. However, little attention has been given to the potential use of rubber as aggregate in pavement application, particularly for CPBs. Also, the few studies that have been conducted on the use of rubber as aggregate in CPBs focused on the use of high value water cement ratios (in the range of 0.40 – 0.65). On the other hand, most commercially made concrete pavement block companies in the world do use small value water cement ratios (in the range of 0.20 – 0.35), especially commercial pavement block companies in Ghana. Therefore, there is the need to assess the possibility of using rubber aggregate in CPBs production with small value water cement ratios. The current research is aimed at investigating the feasibility of using ground vehicular tyre (GVT) as partial replacement for sand in the production of CPBs with small value water cement ratios in Ghana. As previously mentioned, due to the very high toughness of waste tyres, it is expected that adding GVT to CPB mixture in this study can increase the toughness and impact resistance of CPB considerably. Furthermore, the use of waste tyres in CPBs will contribute to providing environmentally friendly solution for the tyre disposal problem in Ghana.

1.3 Aim of the Study

The aim of the study is to investigate the feasibility of using GVT as partial replacement for sand in the production of CPBs with small value water cement ratios.

1.4 Objectives of the Study

In line with the aim set for the study, the following objectives have been formulated:

i. To examine the physical and mechanical properties of rubberized concrete pavement blocks (RCPBs). Physical properties including density and water absorption will be determined. Mechanical properties including compressive strength, flexural strength, and splitting tensile strength will be determined.

ii. To assess the relationship between density and compressive strength, compressive strength and flexural strength, compressive strength and splitting tensile strength, and flexural strength and splitting tensile strength of RCPBs.

iii. To develop models to predict the density and compressive strength of RCPBs which will be produced by this study.

1.5 Significance of the Research

i. The study will contribute to the existing knowledge on RCPBs production.

ii. The study will help the authorities to make decisions on waste tyres problems in Ghana.

iii. The study will help the nation to utilize waste material and reduce the use of natural material in CPB production.

1.6 Limitations of the Study

Certain limitations were identified in this study.

i. The influence of different sizes of tyre on the properties of rubberized concrete pavement blocks was not evaluated in this study because of the difficulties in getting the sizes of tyre required for the study.
ii. Properties like impact resistance, skip resistance, and toughness were not considered in this study due to lack of machines required to conduct such tests.
iii. The effect of long term curing age on the properties of rubberized concrete pavement blocks was not considered because of time limit.

1.7 Scope of the Study

The scope of the study was divided into three parts.

i. Different W/C ratios (0.20, 0.25, 0.30, and 0.35) and GVT content (0%, 10%, 20%, 30%, 40%, 50%, and 60%) were used to prepare the RCPBs. The density and compressive strength of those batches were determined.
ii. W/C ratio of 0.35 was used to produce additional specimens. Properties such as compressive strength, flexural strength, splitting tensile strength, and water absorption were considered at this stage.
iii. Models were developed to predict the density and compressive strength of the produced RCPBs.

CHAPTER TWO

REVIEW OF RELATED LITERATURE

2.0 Introduction

In this chapter, the current state of knowledge and literature pertaining to rubberized concrete is addressed. The term "rubberized concrete" refers to concrete containing rubber and ordinary aggregates. The rubber aggregate can be managed as slit tyre, as shredded or chopped tyre, as ground rubber or as a crumb rubber product. Also in this chapter are the fresh and hardened properties of rubberized concrete. In addition, the production of rubber aggregates and the different surface treatment methods utilized by other researchers are taken into consideration. Included in this chapter is a review of basic understanding and materials used in concrete paving blocks production. Two general methods of manufacture of CPB, pressure and high frequency vibration manufacture methods are first reviewed. Information about the nature of concrete block pavement is also addressed. Advantages and disadvantages between interlocking concrete block, asphalt, and rigid concrete pavement is then compared. Factors affecting the structural performance of concrete block pavement are finally reviewed.

2.1 Rubberized Concrete

The concrete mixed with waste rubber added in different volume proportions is called rubberized concrete and is an infant technology (Kumaran et al., 2008). Partially replacing the coarse or fine aggregate of concrete with waste tyre can improve qualities such as low unit weight, resistance to abrasion, shocks and vibrations, high ductility and so on to the concrete. Again, the incorporation of rubber into concrete results in higher resilience, durability, and elasticity (Eldin & Senouci, 1993; Lee, Burnett, Miller, Postage, & Cuneo, 1993; Toutanji, 1996; Raghavan, Huynh, & Ferraris, 1998; Raghavan, 2000). Constructions that are subjected to impact effect, the use of rubberized concrete will be beneficial due to the altered state of its properties (Kumaran et al., 2008).

2.2 Material Constituents of Rubberized Concrete

2.2.1 Rubber aggregate

Several forms of tyres can be used as rubber aggregate in concrete mixture. These include slit tyre, crumb tyre or ground rubber. Generally, two processing technologies are used to convert scrap tyres into rubber aggregate. These are mechanical grinding and cryogenic grinding. The most common process is the mechanical grinding. In this method, variety of grinding techniques such as cracker mills and granulators are used to breakdown the rubber shred into smaller particles. The steel bead and wire mesh in the tyre are magnetically separated from the crumb during the various stages of granulation, and sieve shakers separate the fibre in the tyre (Cairns, Kew, & Kenny, 2004).

Cryogenic processing on the other hand is carried out at a temperature below the glass transition temperature. This is normally done by freezing scrap tyres using liquid nitrogen. The cooled rubber is extremely brittle and is fed into a cooled loop hammer-mill to be crushed into smaller particles. The steel bead and wire mesh are removed in the similar manner as described in mechanical grinding. The whole process takes place without the presence of oxygen and as a results surface oxidation is not a consideration.

Due to the low temperature used in the process, the rubber derived from the process is not altered from the original material (Cairns et al., 2004).

Several types of rubber aggregates have been used in previous investigations. Buff rubber obtained from mechanical grinding of tyre head were used by (Rostami, Lepore, Silverstrain, & Zundi, 1993; Topcu, 1995). Ali, Amos, and Roberts (1993) and Khatib and Bayomy (1999) used rubber obtained from mechanical grinding of whole tyres. Eldin and Senouci (1993) used two tyres of coarse rubber aggregates, one type was long angular chips obtained by mechanical grinding and the other was round particles produced by cryogenic grinding. Crumb rubber produced from shredding tyres were used by (Taha & Wahab, 2003; Azmi, Mohammed, & Al-Mattarneh, 2008; Ling, 2008; Najim & Hall, 2010; Aules, 2011). Mavroulidou and Figueiredo (2010) used coarse rubber and fine rubber aggregates.

The sizes and grading of rubber aggregates used by various researchers also varied considerably. Ali et al. (1993) used three groups of rubber with a maximum size of less than 4.76 mm. Topcu (1995) graded the rubber into 0 – 1 mm and 1 – 4 mm. Eldin and Senouci (1993) graded their rubber into three groups at maximum size of 38 mm, 25 mm, and 19 mm. Khatib and Bayomy (1999) graded the rubber based on the American Society for Testing and Materials (ASTM), C 136 method. Ling (2008) graded the rubber into 1 – 3 mm, 3 – 5 mm, and combination of both. Mavroulidou and Figueiredo (2010) graded their rubber into 19 – 10 mm and 4.5 – 10 mm. Azmi et al. (2008) graded the rubber into 2 – 2.36 mm. Aules (2011) graded the crumb rubber into 4.75 mm, 2.36 mm, 1.18 mm, 0.6 mm, and 0.15 mm. Taha and Wahab (2003) graded the crumb rubber into 5 – 20 mm.

2.2.1.1 Specific gravity of rubber

Specific gravity is the ratio of the density of a substance to the density of a reference substance. The reference substance is nearly always water for liquids or air for gases. Temperature must be specified for both the sample and the reference. The specific gravity of rubber used in different investigations varied widely. The variations in specific gravity could be due to varying rubber quality (Fattuhi & Clark, 1996). Rostami et al. (1993) and Topcu (1995) used a rubber with a specific gravity of 0.65 and 0.80 respectively. Ali et al. (1993) and Khatib and Bayomy (1999) used rubber with a specific gravity of 1.06 and 1.12 in order.

2.2.1.2 Chemical composition of a tyre

A tyre is an assembly of various components that are built up in drums and then cured in a press under heat and pressure. Heat facilitates a polymerization reaction that cross-links rubber monomers to create long elastic molecules. These polymers create the elastic quality that permits the tyre to be compressed in the area where the tyre contacts the road surface and spring back to its original under high frequency cycles. The fundamental materials of modern tyres are rubber and other compound chemicals. Table 2.1 shows the chemical composition of tyre rubber.

Table 2.1: Chemical composition of tyre rubber (Mavridou & Oikonomou, 2011)

Chemical composition	Range of values for rubber examined (%)	Mean value (%)
Acetone extract	12 - 14	13
Ash content	6, 5 – 7, 5	7
Carbon black	28 – 32	30
Rubber hydrocarbon	48 – 52	50

2.2.2 Aggregates

Rubberized concrete is produced by partially or fully replacing the mineral aggregates with rubber. Therefore, the mineral aggregates are still part of the constituents as in the conventional concrete. Aggregates generally occupy about 70% to 80% of the volume of concrete and can therefore be expected to have an important influence on the properties of concrete. Aggregates are granular materials derived from most natural rocks and sands. In addition to their use as economical filler, aggregates generally provide concrete with better dimensional stability and wear resistance. Based on their sizes, aggregates are divided into coarse and fine aggregates. The coarse aggregate is that retained on the 4.75 mm sieve while the fine aggregate is that passing the same sieve (Sidney, Young, & Darwin, 2003). Aggregates are directly extracted from original sources like river basins or by manufacturing them into desired shapes from the parent rocks in a crusher mill.

Natural aggregates particles are originally formed as part of a large parent mass. This may have been fragmented by natural abrasion or artificially by crushing. Many properties of aggregates depend mainly on the properties of the parent rock. For instance, chemical and mineral composition, specific gravity, hardness, strength, physical and chemical stability, pore structure, and colour. On the other hand, there are some properties possessed by the aggregate but absent in the parent rock; particles shape and size, surface texture, and absorption. All these properties may have a considerable effect on the quality of the concrete, either in the fresh or in the hardened state (Neville, 1996).

2.2.3 Cement

Cement is a generic name that can apply to all binders. The chemical composition of cement can be quite diverse but by far the greatest amount of concrete used today is made with Portland cements (Sidney et al., 2003). The choice of cement for a particular application depends on the availability, the cost, skilled labour force, speed of construction and exigencies of the structure, and its environment (Neville, 1996). Wide varieties of cement have been used to produce rubberized concrete by different researchers. Ling (2008) reported to have used ordinary Portland cement (OPC) in his research. On the other hand, Kumaran et al. (2008) used magnesium oxychloride cement (MOC) and OPC for their research. The results of the compressive and tensile strength tests demonstrated that there is better bonding when MOC is used.

Biel and Lee (1996) also used MOC and OPC for their research. They reported that the type of cement used for rubberized concrete noticeably affects its compressive strength. Recycled tyre rubber aggregates were used in concrete mixture made with MOC and OPC. The percentage substitution of fine aggregate ranged from 0%– 90% by weight. It was observed that 90% loss of compressive strength occurred for both MOC and OPC when 25% of the total aggregate was replaced by rubber. MOC concrete demonstrated approximately 2.5 times the compressive strength of OPC concrete with or without the incorporation of rubber in the concrete. The OPC concrete samples containing 25% rubber by total aggregate volume retained 20% of their splitting tensile strength after an initial failure while the MOC concrete samples with the same rubber content retained 34% of the splitting tensile strength. They further noted that the use of MOC greatly improved the strength and bonding characteristics of rubberized concrete and that structural application could be possible if the rubber content is limited to 17% by total volume of the aggregate.

2.2.4 Water

Water is an imperative ingredient in the production of concrete. It is used for both mixing and curing of concrete. Attention should be given to the quality of water used in concrete. Generally, almost all natural water, fresh water, and water treated for municipals are satisfactory for concrete production.

2.3. Properties of Fresh Rubberized Concrete

2.3.1 Aesthetics

Cairns et al. (2004) observed that rubberized concrete exhibited good aesthetic qualities. The finished surface has a similar appearance to that of ordinary concrete and the finishing of the surface was not problematic. However, they reported that more works is required to smooth the finished surface of the concrete mixture if it contains a high percentage of larger sized rubber aggregate. The authors also found that rubberized concrete did not differ noticeably from that of ordinary concrete in terms of colour.

2.3.2 Air content

The air content in concrete mixtures containing rubber particles is higher than control mixtures. The higher air content of rubberized concrete mixtures may be due to the non-polar nature of rubber aggregates and their ability to entrap air in their jagged surface texture. When non-polar rubber aggregate is added to concrete mixture, it may attract air as it repels water (Danko, Cano, & Pena, 2006). This increase in air voids content would definitely result in reduction in concrete strength of rubberized concrete as in ordinary concrete (Neville, 1996).

Ali et al. (1993) reported that when rubber aggregate was added to the concrete, its air content was increased to about 14%. Khatib and Bayomy (1999) observed that the air content of rubberized concrete increased as the rubber content increased. However, if air gets trapped in the jagged surface of the rubber aggregates, it could cause them to float (Nagdi, 1993). This segregation of rubber aggregate particles has been observed in practice.

2.3.3 Workability

Cairns et al. (2004) observed a reduction in slump when the rubber aggregate content was increased. The slump was close to zero when 40% volume of the aggregate was replaced by rubber. Such mixtures had to be compacted using a mechanical vibrator. The authors reported that mixtures containing fine crumb rubber were however more workable than mixtures containing either coarse rubber aggregate or a combination of crumb rubber and tyre chips.

Batayneh, Marie and Asi (2008) noticed a decrease in slump when the crumb rubber content was increased. The slump was reduced by 93.8% when total volume of the fine aggregate was replaced by crumb rubber. Despite the decrease in measured slump, observation during mixing and casting showed that increasing the crumb content in the mix still produced a workable mix in comparison with the control mix. However, Azmi et al. (2008) reported that the workability of Portland concrete can be improved when crumb rubber is added. The mix design for water cement ratio of 0.68 gave the highest workability as compared to other mix designs. The slump value increased approximately about 10% as the crumb rubber content increased from 0 to 30%.

2.4 Properties of Hardened Rubberized Concrete

2.4.1 Density

The replacement of natural aggregate with rubber aggregates tends to lower the density of the concrete. This reduction is attributed to the low specific gravity of rubber aggregate compared to ordinary aggregate (Ling, 2008). Eldin and Senouci (1993) reported a decrease of 25% in density when coarse rubber aggregate was used to replace coarse aggregate. Li et al. (1998) noticed that the density of rubberized concrete was lowered by approximately 10% when 35% volume of sand was replaced by crumb rubber. Rostami et al. (1993) observed a reduction of 77% in density when the maximum amount of rubber aggregate was used in the investigation. Topcu (1995) reported that the density of rubberized concrete was reduced by 87% when the maximum amount of rubber aggregate was used.

Ling (2011) reported that the hardened density of rubberized concrete pavement blocks (RCPB) reduced by about 8% of the normal concrete when 50% volume of the sand was replaced by crumb irrespective of the W/C ratio used. Mavroulidou and Figueiredo (2010) observed that the density of rubberized concrete reduced about 75% when the 40% of mineral aggregate was replaced by coarse rubber aggregate. On the other hand, the density was lowered about 76% when the 40% of the fine mineral aggregate was replaced by fine rubber aggregate.

Najim and Hall (2010) studies shown that, rubberized concrete produces low unit weight mixes with higher air contents which are easier to pump. Reduction in dry density was observed due to replacement with both coarse and fine aggregates with crumb rubber. Kamil, Kalouh, George, Way, and Zhu (2005) analysed the properties of crumb rubber concrete. The unit weight of the concrete mix decrease approximately 6 pcf for every 50 Ibs of crumb rubber added. Kumaran et al. (2008) also reported that reduction in the unit weight of the rubberized concrete mix increases as the percentage of the crumb rubber increases. However, Khatib and Bayomy (1999) reported that decrease in unit weight of rubberized concrete is negligible when rubber content is lowered than 10% – 20% of the total aggregate volume.

2.4.2 Compressive strength

Several authors have reported on the compressive strength of rubberizes concrete. It is observed that increase in rubber aggregate content reduces the compressive strength of rubberized concrete. Results of various studies also indicate that the size, proportions, and surface texture of rubber particles noticeably affect the compressive strength of rubberized concrete mixtures.

Eldin and Senouci (1993) reported that concrete mixture containing tyre chips and crumb rubber aggregates demonstrated lower compressive strength than ordinary concrete. Reduction in compressive strength of about 85% was observed when coarse rubber chips were used to fully replace coarse aggregate. However, a decrease of about 65% in compressive strength was observed when fine aggregate was fully replaced by crumb rubber. Topcu (1995) also reported that the incorporation of coarse rubber in concrete lowered the compressive strength more than the addition of crumb rubber aggregate. About 50% reduction in cylinder and cube compressive strength was observed when fine rubber aggregate was used. However, about 60% and 80% decrease in compressive strength were observed for cylinder and cube respectively when coarse rubber aggregate was used.

Toutanji (1996) conducted experiments to investigate the effect of four different contents of rubber aggregates with a maximum size of 12.7 mm. The rubber aggregates were used to replace the coarse aggregate at 25%, 50%, 75%, and 100% by volume. It was discovered that the addition of rubber aggregate in concrete mixture reduced its compressive strength up to 75%. Khatib and Bayomy (1999) investigated the effect of crumb rubber and tyre chips on concrete. The authors reported that the compressive strength of rubberized concrete was reduced by 93% when coarse aggregate was fully replaced by tyre chips and by 90% when fine aggregate was fully replaced by crumb rubber.

Ling (2008) reported that concrete mixture containing crumb rubber exhibited lower compressive strength than ordinary concrete mix. Reduction in compressive strength of about 52% was observed when 30% volume of the total sand was replaced with crumb rubber. Mavroulidou and Figueiredo (2010) conducted experiments to investigate the effect of two different rubber aggregates on concrete mixtures. Fine rubber aggregates and coarse rubber aggregates were used as partial replacement for fine and coarse mineral aggregates respectively. A reduction in compressive strength of 88.3% was observed when 40% of the coarse mineral aggregate was replaced by coarse rubber aggregate. On the other hand, a reduction of 92.6% was observed when fine mineral aggregate was partially replaced by 40% fine rubber aggregate.

Azmi et al. (2008) observed that there was a decrease of about 35% in compressive strength value when 30% of the fine aggregate was replaced with crumb rubber. Aules (2011) reported that mortar mixture containing crumb rubber demonstrated lower compressive strength than regular Portland cement mortar. A reduction in compressive strength of up to 68% was noticed when 30% of the sand was replaced with crumb rubber. This could be due to the weak bond between the crumb rubber aggregate and the cement paste. Sgobba, Marano, Borsa, and Molfetta (2010) reported that the compressive strength of concrete mixture reduced up to 85% when the coarse aggregates were replaced by crumb rubber. Fattuhi and Clark (1996) and Aiello and Leuzzi (2010) reported that the incorporation of waste tyre as fine and coarse aggregates in concrete reduced its compressive strength. It was shown that the reduction in compressive strength with replacement with coarse rubber aggregate was higher than that of fine rubber aggregates.

Schimizze, Nelson, Amirkhanian, and Murden (1994) developed two rubberized concrete mixtures using fine rubber granular in one mix and coarse rubber granular in the other. The results indicated a reduction in compressive strength of about 50% for both mixtures with respect to the control mixture. Kamil et al. (2005) analysed the properties of crumb rubber concrete. The study exhibited that compressive strength decreased as the rubber content increased. The strength reduction could be attributed to the entrapped air, which increased with the rubber content. Kumaran et al. (2008) conducted a test on rubberized concrete behaviour. They reported that the compressive strength reduced as the rubber content increased. A reduction of 85% in compressive strength was observed as compared to the control mix. Taha and Waha (2003) conducted an experiment by substituting 100% volume of coarse aggregate by rubber. The results showed that the compressive strength was decreased by 75%. They related their reduction to variation of the shape and the size of transmission zone from the vicinity of rubber crumbs.

However, Oivares, Barluenga, Bollati, and Witoszek (2002) observed that replacing 3.5% and 5% volume of recycled rubber in cement matrix has no significant effect on the compressive strength. In most studies a reduction in compressive strength were observed with the addition of rubber aggregate in the concrete mix but there is still a possibility of greatly improving the compressive by using de-airing agent (Neville, 1996).

2.4.3 Toughness and impact resistance

Although, the reduction in strength of rubberized concrete may limit their use in some structural applications, previous researchers have suggested that rubberized concrete exhibited improved toughness and a less brittle failure mode (Ling, 2008).

Eldin and Senouci (1996) observed that the failure mode of concrete mixture containing rubber content was gradual as opposed to brittle. Biel and Lee (1996) reported that the failure of concrete specimens containing 30%, 45%, and 60% rubber as replacement for fine aggregate occurred gradually while the failure of the control specimens was explosive leaving specimens into several pieces.

Raghavan et al. (1998) reported that mortar specimens with rubber shreds were able to withstand additional load after peak load. The specimens were not separated into two pieces under the failure flexural load because of bridging of cracks by rubber shreds.

However, specimens made with granular rubber particles broke into two pieces at the failure load. This demonstrated that post-crack strength seemed to be enhanced when rubber shreds are used instead of granular rubber. Khatib and Bayomy (1999) reported that as the rubber content increased, the rubberized concrete tends to fail gradually. During the compressive loading of a rubber content of 60% by total aggregate volume, the failure specimens was capable of absorbing significant plastic energy and withstanding large deformation without full disintegration.

Tantala, Lepore, and Zandi (1996) investigated a comparative study of the toughness of a control concrete mixture and rubberized concrete mixture with 5% and 10% buff rubber by volume of the coarse aggregate. It was found that the toughness of both rubberized concrete mixtures was higher than the control concrete mixture. However, the toughness of rubberized concrete with 10% buff rubber was lower than that of 5% buff rubber because of the decreasing ultimate compressive strength. Toutanji (1996) examined the effect of rubber aggregate on concrete. It was observed that the specimens containing rubber aggregate exhibited a ductile mode of failure as compared to the controlled specimens.

Aules (2011) reported that mortar mixture with crumb rubber was able to withstand a large tensile deformation. This could be attributed to the rubber particles behaviour which acts like small spring. Khaloo, Dehestani, and Rahmatabadi (2008) conducted an experiment and it was observed that the rubberized concrete under compressive test demonstrated a ductile behaviour during failure. Zheng, Huo, and Yuan (2008) calculated brittleness index value on hysteresis loops which were obtained by loading, unloading, and reloading the specimens when coarse aggregate were replaced by ground rubber in different replacement levels. The results showed that values of both crushed and ground rubberized concrete were lower than normal concrete indicating higher ductility performance than normal concrete. The optimal ground rubber content recommended was 15% and 30% for satisfactory brittleness index and compressive strength values. Another deformation studies conducted by Topcu (1997) and Topcu and Avacular (1997) demonstrated that rubberized concrete was ductile and capable of undergoing higher deformation at fracture and absorb more energy.

Garrick (2004) showed the analysis of waste tyre modified concrete. Coarse aggregates were replaced by 15% volume waste tyre in concrete mix. The results indicated that there was an increase in toughness, plastic deformation, and impact resistance. The control specimen disintegrated when peak load was reached while the rubberized concrete has a considerable deformation without disintegration due to the bridging caused by the tyre.

2.4.4 Tensile strength

Research indicated that tensile strength of rubberized concrete reduces as the rubber content increases. Studies also indicate that the size, proportions, and surface texture of rubber particles affect the tensile strength of rubberized concrete mixtures. Eldin and Senouci (1993) reported that concrete mixture with tyre chips and crumb rubber aggregates exhibited lower splitting tensile strength than regular Portland cement concrete. Reduction in strength approximately 50% of the splitting tensile strength was observed when coarse aggregate was fully replaced by coarse crumb chips. Also a smaller reduction of about 50% in splitting tensile strength was observed when fine aggregate was fully replaced by fine crumb rubber.

Topcu (1995) reported that the addition of coarse rubber chips in concrete lowered the tensile strength more than the addition of fine crumb rubber aggregate. About 64% decrease in tensile strength was observed in concrete mixed with fine rubber aggregate. However, a reduction up to 74% in tensile strength was noticed when coarse rubber aggregate was used. Ling, Nor, Hainin, and Lim (2010) reported that the incorporation of rubber in RCPBs reduced its splitting tensile strength. It was observed that the tensile strength of the RCPB was reduced by about 86% when 30% volume of crumb rubber was used to replace fine aggregate.

Mavroulidou and Figueiredo (2010) found that the tensile strength of rubberized concrete decreased as the rubber content increased. The tensile strength of the rubberized concrete was reduced by 32.5% and 30% for 40% coarse rubber aggregate replacement and 40% fine rubber aggregate replacement respectively for a curing period of 28 days. Azmi et al. (2010) studies demonstrated that the splitting tensile strength reduced with the increase of the crumb rubber content. There was a reduction about 15% in splitting tensile value when crumb rubber content increased from 0% to 30%. The reduction in tensile strength could be attributed to the weak bond between the rubber particles and the cement paste in the mix.

2.4.5 Flexural strength

Studies show that reduction in flexural strength of rubberized concrete increases as the rubber content increases. Toutanji (1996) conducted experiments to investigate the effect of four different contents of rubber aggregate on concrete mixtures. The rubber was used to replace the coarse aggregate at 25%, 50%, 75%, and 100% by volume. It was discovered that the inclusion of the rubber aggregate in the concrete produced a smaller reduction of about 35% in flexural strength as compare to the controlled specimens.

Khatib and Bayomy (1999) investigated the effect of crumb rubber and tyre chips on concrete. It was found that the flexural strength of the rubberized concrete was lowered about 90% when fine aggregate was fully replaced by rubber crumb and 93% when coarse aggregate was used. Ling et al. (2010) conducted a test on the effect of rubber on flexural strength of RCPB. The results showed that the flexural strength slightly improved by approximately 10% as compare to the control specimen when the sand was replaced by 10% rubber (10-RCPB). The improvement in flexural strength was limited to samples with relatively small rubber aggregate content. However, at higher volume of sand replaced by crumb rubber, the flexural strength was reduced by 32% and 48% for 20-RCPB and 30-RCPB respectively. Mavroulidou and Figueiredo (2010) reported that concrete mixture with coarse rubber aggregate and fine rubber aggregate demonstrated a slight reduction in the modulus of rupture as compared to the control mixes. A decrease of about 12% and 22% was observed when coarse rubber aggregate and fine rubber aggregate were used in order.

Azmi et al. (2008) observed that flexural strength of rubberized concrete decreased with the increased of the crumb rubber content from 0% to 30%. The mix design for water cement ratio 0.41 showed the highest loss in flexural strength of about 20% as compared with W/C ratios 0.57 and 0.68 which showed loss of about 5% and 8% respectively. Aules (2011) reported that the flexural strength of rubberized concrete decreased as the rubber content increased from 0% to 30% in a similar manner to that observed in the compressive strength. However, the reduction in flexural strength was lower than that of the compressive strength.

2.4.6 Modulus of elasticity

Goulias and Ali (1997) conducted an experiment and was observed that the modulus of elasticity decreased with an increased in the rubber content indicating that a less stiff and less brittle material was obtained. Mavroulidou and Figueiredo (2010) studies demonstrated that modulus of elasticity of rubberized aggregate reduced when the rubber aggregate content increased. The modulus of elasticity for the mixture with coarse rubber aggregate was lowered about 9% when 10% coarse rubber aggregate was used to replace coarse mineral aggregate while approximately 18% reduction was observed when 10% fine rubber aggregate was used to substitute fine mineral aggregate.

Azmi et al. (2008) reported that the incorporation of rubber into concrete decreased its modulus of elasticity. There was a reduction approximately 30% in modulus of elasticity value when crumb rubber content was increased from 0% to 30%. The reduction in modulus of elasticity may be attributed to the inclusion of crumb rubber particles in the mix which affected the internal structure of the composite material, producing a reduction of strength and a decrease in stiffness.

Schimizze et al. (1994) developed two rubberized concrete mixes using fine rubber aggregate in one mix and coarse rubber granular in second. It was observed that the elastic modulus of the mix containing coarse rubber granular was reduced to about 72% of that of the control mix, whereas the mix containing fine rubber granular showed a reduction in the elastic modulus to about 47% of that of the control mixture. The reduction in elastic modulus indicates higher flexibility, which may be viewed as a positive gain in rubberized concrete mix used as stabilized base layers in flexible pavements.

2.4.7 Water absorption

Ling, Nor, and Lim (2010) using recycled waste tyres in CPBs conducted a research to investigate the effect of rubber on the water absorption of RCPB. It was discovered that the water absorption of the RCPB increased by about 25% when fine aggregate was replaced by 30% crumb rubber. This could be attributed to the rate at which voids in RCPBs increase as the rubber content increases. However, for water absorption value after immersion and boiling in water, the control specimens showed higher values as compared to the CPBs containing crumb rubber. The authors reported that this may be due to the high level of compaction applied to the CPBs containing crumb rubber, the rubber particles helped fill pores in the concrete mixture because rubber particles are much softer than the surrounding particles.

2.5. Relationship between Properties of RCPBs

Ling (2008) reported that there was a positive correlation between flexural strength and splitting tensile strength, and compressive strength and splitting tensile strength of RCPBs. Ling et al. (2010) observed that there was a linear correlation between compressive strength and flexural strength of RCPBs. Ling (2012) also reported that there was a linear relationship between density and compressive strength of RCPB. A decrease in density of RCPB resulted in a decrease in compressive strength for both plant-made and manually made RCPBs.

2.6 Effect of Curing Age on Flexural Strength

Ling (2008) mentioned that the flexural strength of RCPB increased as the curing age increased. The flexural strength increased about 25% when the curing age moved from 7 days to 28 days for 20% replacement of crumb rubber. Azmi et al. (2008) also reported that the flexural strength of crumb rubber concrete increased as the curing age increased. With 10% replacement of sand with crumb rubber, the flexural strength of the rubberized concrete increased from 7.1 N/mm^2 to 9.4 N/mm^2 when the curing age moved from 7 days to 28 days for W/C ratio of 0.4.

2.7 Effect of Curing Age on Splitting Tensile Strength

Ling (2008) mentioned that the splitting tensile strength of RCPB increased about 24% when the curing age moved from 7 days to 28 days. An increase of about 21% in splitting tensile strength of rubberized concrete was reported by Mavroulidou and Figueiredo (2010) when the curing age moved from 7 days to 28 days.

2.8 Effect of Curing Age on Compressive Strength

Azmi et al. (2008) noticed that compressive strength of rubberized concrete increased as the curing age increased regardless of the volume of crumb rubber and the W/C ratio used. The compressive strength increased from 17.8% N/mm^2 to 24.4 N/mm^2 for a 7 day curing and a 28 day curing respectively. Ling (2008) also reported that the compressive strength of RCPB increased as the curing age increased irrespective of the content of crumb rubber and W/C ratio used. The compressive strength was raised from 29MPa to 33MPa for a 7 day curing and a 28 day curing in order. The reduction in strength for the 7 day curing may be attributed to the insufficient water the cement paste received during the hydration period.

2.9 Predicting the Density and Compressive Strength of RCPBs

Ling (2011) developed equations to predict the density and compressive strength of RCPBs. The independent variables for his predictions were rubber and W/C ratio. The effect of rubber and W/C ratio on the predicting the density and the compressive strength were found to be statistically significant.

2.10 Effect of Treatment and Surface Texture of Rubber Aggregate

Studies have demonstrated that if the rubber particles have rougher surface or are given a pre-treatment, then better and improved bonding may be developed with the surrounding matrix and therefore may result in higher compressive strength (Ling, 2008). Naik and Singh (1991) reported that pre-treatment may vary from washing rubber particles with water to acid etching, plasma pre-treatment and various agents. The rubber particles were immersed in alkaline solution (NaOH) for 5 minutes and then washed with water. The authors observed that the treatment improved the strength of concrete having rubber particles. Eldin and Senouci (1993) soaked and thoroughly washed rubber particles with water in order to remove contaminants. They observed that compressive strength of concrete containing water-washed rubber particles was 16% higher than concrete containing untreated rubber aggregates.

Serge and Joekes (2000) used saturated NaOH solution to treat waste tyre rubber powder. They found that NaOH surface treatment increased rubber/cement paste interfacial bonding strength and resulted in an improvement in strength and toughness in waste tyre powder modified cement mortar. Guoqiang et al. (2004) conducted an experiment on the use of rubber chips and fibres in the production of CPBs. The tyre surfaces were treated with saturated NaOH solution and physical anchorage by drilling hole at the centre of the chips was also investigated. They concluded that fibres performed better than chips. NaOH surface treatment does not work for large sized tyre chips, using physical anchorage had some effect. Also, an attempt to improve the surface of the rubber aggregate by treatment with cement paste and Methocel cellulose ether solution was tried by Li et al. (1998). The rubber particles used were untreated and pre-treatment with either cement paste or coated with Methocel cellulose ether solution. Coating rubber particles with cement paste increased the compressive strength of the rubberized concrete.

Use of organic sulphur compounds to modify the surface texture of rubber was demonstrated by Chou et al. (2010). Organic sulphur compounds improved the hydrophilic behaviour of the rubber. Also, compressive, tensile, and flexural strengths of the treated samples increased considerably. Pelisse, Zavarise, Longo, and Bernardin (2011) investigated the effect of recycled rubber washed with sodium hydroxide and silica fume along with ligno-sulphate admixture on concrete. It was observed that the rubberized concrete samples exhibited a reduction in porosity due to hydrophilic effect.

2.11 Application and Advantages of Rubberized Concrete over Ordinary Concrete

Rubberized concrete are affordable, cost effective and can withstand more pressure, impact and temperature when compare with ordinary concrete (Kumaran et al., 2008). It is observed that the rubber modified concrete (RMC) are very weak in compressive and tensile strengths. But they have good water resistance with low absorption, improved acid resistance, low shrinkage, high impact resistance, and excellent sound and thermal insulation. Studies shows that crumb rubber concrete (CRC) specimens remained intact after failure compare to a conventional concrete mix. Such behaviour may be beneficial for a structure that required good impact resistance properties. The impact resistance of rubberized concrete was higher and it was particularly evident in concrete samples aggregate with thick rubber (Kamil et al., 2005).

Moreover the unique qualities of rubberized concrete will find new areas of usage in highway constructions as a shock absorber, in sound barriers as a sound absorber, and also in buildings such as earthquake shock wave absorber. It reduces plastic shrinkage cracking and reduces the vulnerability of concrete to catastrophic failure (Kumaran et al., 2008). Currently, the waste tyre modified concrete is used in precast sidewalk panel, non-load bearing walls in buildings and precast roof for green buildings (Tomosawa, Noguchi, & Tamura, 2005). It can be widely used for development related projects such as roadways or road intersections, recreational court and pathways, and skid resistant ramps (Kamil et al., 2005). Within this new property, it is projected that these concretes can be used in architectural applications such as nailing concrete, where high strength is not necessary, in wall panels that required low unit weight in construction elements and

Jersey barriers that are subjected to impact, in rail roads to fix rails to the ground (Topcu, 1995).

Rubberized concrete can also be used in non-load bearing members such as lightweight concrete walls, building facades, or other light architectural units, thus the waste tyre modified concrete mixes could give a viable alternative to the normal weight concrete (Khatib & Bayomy, 1999). Rubberized concrete could be used in places where cement-stabilized aggregate bases are needed, particularly under flexible pavements. The other viable applications will be suited for use in areas where repeated freezing and thawing occur and can be poured in larger sheets than conventional concrete. The tennis courts can now be poured in a single slab, eliminating section lines which must be smoothed after curing. Roofing tiles and other concrete products can now be made lighter with rubberized concrete (Kamil, Carlson, Way, & Belshe, 2004). It may also be used in runways and taxi ways in the airport, industrial flooring and even as structural member.

2.12 Cost Consideration of Rubberized Concrete

An important factor when dealing with the acceptability of recycled material is the cost versus the gained benefits. An investigation to the cost consideration of rubberized concrete was carried out by Cairns et al. (2004). This showed that at the time of the investigation, recycled rubber aggregates for concrete were more expensive than the mineral aggregate to be replaced. This could present a problem for the acceptance of rubberized concrete based on cost issues. The authors claimed however that the economics of using recycling rubber in concrete (including the production costs) would be expected to change as the market potential of this product develops and the demand of recycled rubber increases. The authors also pointed out that the processing requirements for rubber aggregates used in concrete are less stringent than for other applications, which would further reduce the cost for rubberized concrete block production and hence giving good prospects for this application (Cairns et al., 2004). This shows promise for the future commercial application of rubber in a large range of concrete products.

2.13. Material Constituents of Concrete Pavement Blocks

2.13.1 Cement

The cement used for the production of CPBs in many countries is the ordinary Portland cement (Ghafoori & Mathis, 1998; Poon, Kou, & Lam, 2002; Poon & Chan, 2006). American Society for Testing and Materials (ASTM) C 150 defines Portland cement as "hydraulic cement (cement that not only hardens by reacting with water but also forms a water-resistant product) produced by pulverizing clinkers consisting essentially of hydraulic calcium silicates, usually containing one or more of the forms of calcium sulphate as an inter ground addition." Clinkers are nodules (diameters, 0.2-1.0 inch [5–25 mm]) of a sintered material that is produced when a raw mixture of predetermined composition is heated to high temperature. The low cost and widespread availability of the limestone, shales, and other naturally occurring materials make Portland cement one of the lowest-cost materials widely used over the last century throughout the world.

Portland cement clinker is made by heating, in a kiln, a homogeneous mixture of raw materials to a calcining temperature, which is about 1450 °C for modern cements. The aluminium oxide and iron oxide are present as a flux and contribute little to the strength. For special cements, such as Low Heat (LH) and Sulphate Resistant (SR) types, it is necessary to limit the amount of tricalcium aluminate ($3\ CaO \cdot Al_2O_3$) formed. The major raw material for the clinker-making is usually limestone ($CaCO_3$) mixed with a second material containing clay as source of alumino-silicate. Normally, an impure limestone which contains clay is used. The $CaCO_3$ content of these lime stones can be as low as 80%. Secondary raw materials (materials in the raw mix other than limestone) depend on the purity of the limestone. Some of the materials used are clay, shale, sand, iron ore, bauxite, fly ash and slag (Wikipedia, 2012).

Portland cement was developed from natural cements made in Britain in the early part of the nineteenth century, and its name was derived from its similarity to Portland stone, a type of building stone that was quarried on the Isle of Portland in Dorset, England. Joseph Aspdin, a British bricklayer from Leeds, is considered to be the originator of Portland cement. A process for the manufacture of Portland cement was patented in 1824 (Gillberg, Jonsson, & Tillman, 1999). Table 2.2 shows the constituents of ordinary Portland cement.

Table 2.2: Typical constituents of Portland cement (Wikipedia, 2012)

Constituents	Mass %
Calcium oxide, CaO	61-67%
Silicon dioxide, SiO_2	19-23%
Aluminium oxide, Al_2O_3	2.5-6%
Ferric oxide, Fe_2O_3	0-6%
Sulphate	1.5-4.5%

2.13.1.1 Types of Portland cement

There are five types of Portland cements with variations of the first three according to ASTM C150.

2.13.1.1.1 Type I

Type I Portland cement is known as common or general purpose cement. It is generally assumed unless another type is specified. It is commonly used for general construction especially when making precast and precast-prestressed concrete that is not to be in contact with soils or ground water. The typical compound compositions of this type are: 55% (C3S), 19% (C2S), 10% (C3A), 7% (C4AF), 2.8% MgO, 2.9% (SO3), 1.0% Ignition loss, and 1.0% free CaO. A limitation on the composition is that the (C3A) shall not exceed fifteen percent.

2.13.1.1.2 Type II

Type II is intended to have moderate sulphate resistance with or without moderate heat of hydration. This type of cement costs about the same as Type I. Its typical compound composition is: 51% (C3S), 24% (C2S), 6% (C3A), 11% (C4AF), 2.9% MgO, 2.5% (SO3), 0.8% Ignition loss, and 1.0% free CaO. A limitation on the composition is that the (C3A) shall not exceed eight percent which reduces its vulnerability to sulphates. This type is for general construction that is exposed to moderate sulphate attack and is meant for use when concrete is in contact with soils and ground water.

2.13.1.1.3 Type III

Type III has relatively high early strength. Its typical compound composition is: 57% (C3S), 19% (C2S), 10% (C3A), 7% (C4AF), 3.0% MgO, 3.1% (SO3), 0.9% Ignition loss, and 1.3% free CaO. This cement is similar to Type I, but ground finer. Some manufacturers make a separate clinker with higher C3S and/or C3A content, but this is increasingly rare, and the general purpose clinker is usually used, ground to a specific surface typically 50% - 80% higher. The gypsum level may also be increased a small amount. This gives the concrete using this type of cement a three day compressive strength equal to the seven day compressive strength of types I and II. Its seven day compressive strength is almost equal to types I and II 28 day compressive strengths. The only downside is that the six month strength of type III is the same or slightly less than that of types I and II. Therefore the long-term strength is sacrificed a little. It is usually used for precast concrete manufacture, where high 1-day strength allows fast turnover of moulds. It may also be used in emergency construction and repairs and construction of machine bases and gate installations.

2.13.1.1.4 Type IV

Type IV Portland cement is generally known for its low heat of hydration. Its typical compound composition is: 28% (C3S), 49% (C2S), 4% (C3A), 12% (C4AF), 1.8% MgO, 1.9% (SO3), 0.9% Ignition loss, and 0.8% free CaO. The percentages of (C2S) and (C4AF) are relatively high and (C3S) and (C3A) are relatively low. A limitation on this type is that the maximum percentage of (C3A) is seven, and the maximum percentage of (C3S) is thirty-five. This causes the heat given off by the hydration reaction to develop at a slower rate. However, as a consequence the strength of the concrete develops slowly. After one or two years the strength is higher than the other types after full curing. This cement is used for very large concrete structures, such as dams, which have a low surface to volume ratio. This type of cement is generally not stocked by manufacturers but some might consider a large special order. This type of cement has not been made for many years, because Portland-pozzolan cements and ground granulated blast furnace slag addition offer a cheaper and more reliable alternative.

2.13.1.1.5 Type V

Type V is used where sulphate resistance is important. Its typical compound composition is: 38% (C3S), 43% (C2S), 4% (C3A), 9% (C4AF), 1.9% MgO, 1.8% (SO3), 0.9% Ignition loss, and 0.8% free CaO. This cement has a very low (C3A) composition which accounts for its high sulphate resistance. The maximum content of (C3A) allowed is five percent for Type V Portland cement. Another limitation is that the (C4AF) + 2 (C3A) compositions cannot exceed twenty percent. This type is used in concrete that is to be exposed to alkali soil and ground water sulphates which react with (C3A) causing disruptive expansion.

2.13.1.1.6 Types Ia, IIa, and IIIa

Types Ia, IIa, and IIIa have the same composition as types I, II, and III respectively. The only difference is that in Ia, IIa, and IIIa an air-entraining agent is ground into the mix. The air-entrainment must meet the minimum and maximum optional specification found in the ASTM manual. They are a poor approach to air-entrainment which improves resistance to freezing under low temperatures.

2.13.1.1.7 Types II (MH) and II (MH) a

Types II (MH) and II (MH) a have recently been added with a similar composition as types II and IIa but with a mild heat.

2.13.2 Coarse aggregate

The properties of coarse aggregate can affect the various properties of concrete. The coarse aggregate used should comply with the requirement of ASTM C33. The surface characteristics of coarse aggregate particles of all sizes have an important influence on the properties of concrete pavement blocks. There is no specialty in the type of mineral aggregate used in concrete pavement blocks. The discussion in Section 2.2.2 of this literature is also applicable here.

2.13.3 Fine aggregate

Fine aggregate should be free from unwanted materials. It is essential that the fine aggregate does not contain more than 25% of acid soluble material in that fraction retained or passing the 600 micron sieve (Ling, 2008). The discussion in Section 2.2.2 of this literature is applicable here.

2.13.4 Water

No special considerations are necessary for the use of water in the production of CPBs. The discussion in Section 2.2.4 of this literature is also applicable for this part.

2.14 Methods of Manufacturing Concrete Pavement Blocks

There are two general methods of manufacturing CPBs (Ling, 2008). These methods are pressure only and high frequency vibration. Both of these methods depend on compaction of the particles of the aggregate and cement content in the mix.

2.14.1 Pressure manufacture

Figure 2.1 demonstrates the use of pressure in manufacturing CPB in steel moulds with internal dimensions of 200 mm long, 100 mm wide, and 60 mm high (Poon & Chan, 2006). The mixture was put into the mould in three layers and compaction was applied with the help of hammer and a wood stem. Trowel was then used to remove the excess materials. Finally, a compaction force was applied at the same rate for 60 seconds.

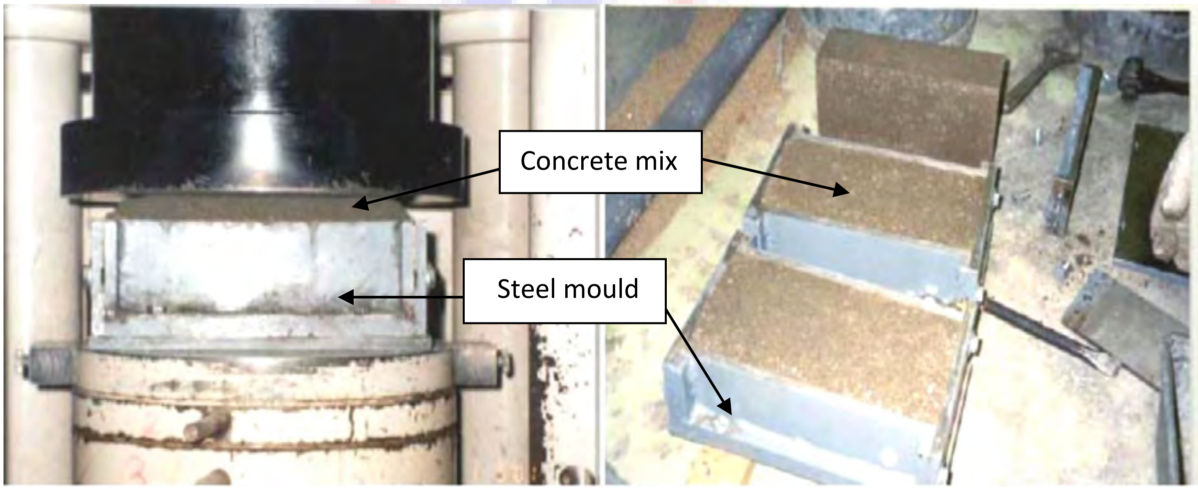


Figure 2.1: During and after fabrication of CPB specimens (Poon and Chan, 2006).

2.14.2 High frequency vibration manufacture

Development of plants specifically for the production of dry CPBs have been considered throughout the twentieth century. Concrete products of high and uniform standard are being produced as results of these modern machines. Current manufacturing practice used in the moulding of CPBs can lead to products with high density and strength, low permeability, and inadequate structure (Ghafoori & Mathis, 1998).

Holt and Raivio (2005) used an intensive compaction tester (ICT-1000R) to simulate CPB manufacturing (Figure 2.2). The ICT was used to compact the mixture materials with a shear-compaction principle, using shear movement and pressure to closely pack the particles over a number of cycles. The ICT was calibrated with a sample pressure of 100 KPa, a gyratory angle of 40 Mrad and a speed of 1.0 hertz, which represented a cycle length of about 1s. Compacted CPBs were manufactured in a similar method with vibration and pressure to achieve the high-density concrete.

Figure 2.2: Tray of CPB moving out of compaction machine in factory (Holt and Raivio, 2005)

2.15 Nature of Concrete Block Pavement

Figure 2.3 illustrates the structure of a CPB. Under the CPB, the pavement is usually made up of a compacted base and sometimes sub-base laid over a compacted sub-grade.

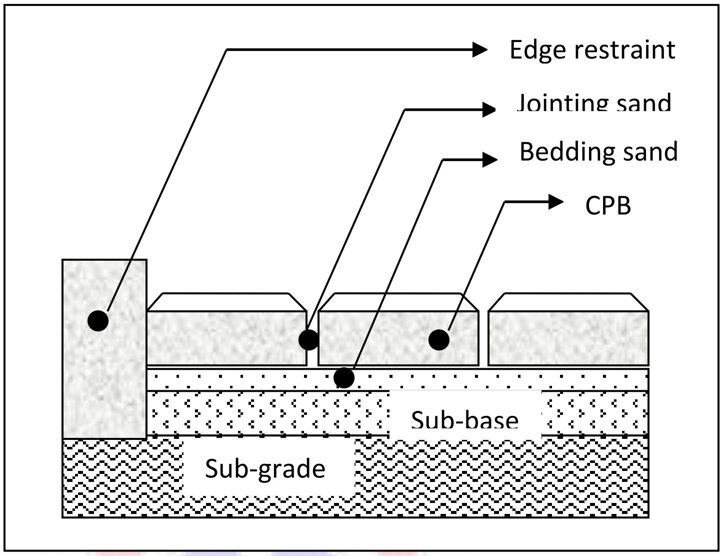


Figure 2.3: Principal elements of a concrete block pavement (Ling, 2008)

Referring to Figure 2.3, the CPBs are put on a 20 mm to 40 mm bedding sand. The joints between the spaces are filled with sand. The sand in the joints facilitates the pavements rotating and wedging together and the generation of horizontal forces between the pavements. The presence of sand in the joints provides two additional advantages. First, the problem of surface reflection cracking caused by base deterioration is largely eliminated. Second, it makes it feasible to remove and relay any part of the pavement. This ensures easy access to buried services, permits recycling of the CPB and reduces maintenances costs (Ling, 2008).

2.16 Advantages and Disadvantages of Concrete Block Pavement

2.16.1 Manufacture of CPB units

Concrete pavement blocks can be produced to achieve excellent dimensional and strength tolerances. As a result pavement blocks tend to be a much more consistent product than most other pavement materials. In order to realise these benefits, complex CPB making machines need to be used. Hand methods of production usually produce inferior products (Ling, 2008).

2.16.2 Construction

Concrete pavement blocks are usually laid by hand using simple construction equipment. However, mechanised laying is also feasible. In general, block pavement cannot be made as rapidly as machine-laid rigid pavements. This disadvantage is offset by the fact that block pavements may be opened to traffic immediately after construction. In other words the delays associated with the curing of conventional rigid concrete pavements are avoided (Ling, 2008).

2.16.3 Operation

Concrete block pavements have a number of operational advantages over other types of flexible pavements. Especially, they can be made to be highly resistance to both punching loads and horizontal shear forces generated by the braking slewing or acceleration of heavy vehicles. Unlike asphaltic surfacing, concrete block pavements have a high resistance to flue and oil spillage and generally a long service life. The main operational limitation on CBPs is that the pavements tend to be best suited for traffic speeds below 70 Km/h (Ling, 2008).

2.16.4 Maintenance

The performance of the sub-base and sub-grade usually determined the life of the CBPs. Shackel (1990) reported that pavements can stay over 20 years. Maintenance cost can be kept low because it is possible to replace any faulty CBP without destroying the whole construction. The wide range of colours interlocking CPBs offer unique aesthetic benefits when compare to other types of pavements. Line marking and traffic control making can be permanently incorporated in concrete block pavement by the use of colour CPB (Ling, 2008). This can reduce road maintenance cost.

2.17 Factors Affecting the Structural Performance of Concrete Block Pavement

The design and construction of a concrete block pavement (CBP) depends on the CPB themselves. The factors that affect the performance of CBP are listed in Table 2.3 and discussed in detail.

Table 2.3: Factors affecting the performance of concrete block pavement (Ling, 2008)

Pavement component	Factors affecting response to traffic
Concrete pavement blocks (CPBs)	Shape Size Thickness Laying pattern
Sand	Thickness Grading Angularity Moisture content
Base and sub-base	Material Thickness
Sub-grade	Material type Strength (bearing capacity

2.17.1 Shape and size of the concrete pavement block

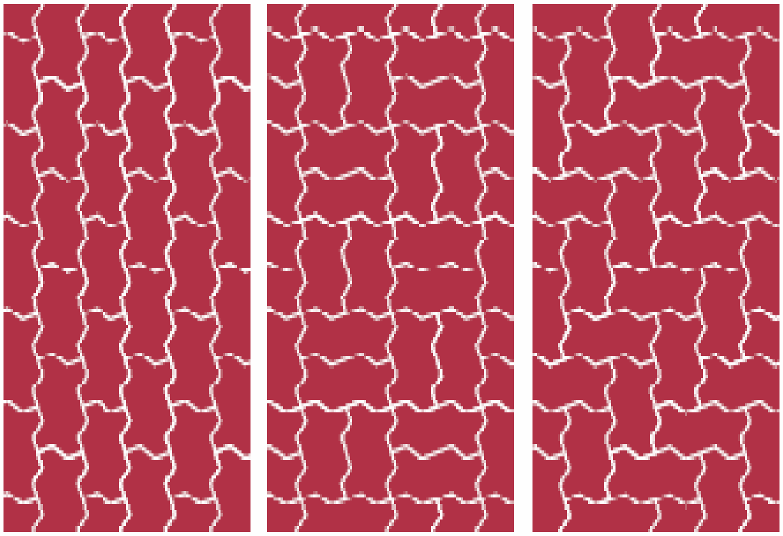
Knapton (1976) reported that block shape had no influence on the load-distributing performance of concrete block pavement. However, contradictory reports were given by (Shackel, 1979a; Rollings, 1982). Knapton and Barber (1979) also postulated that the shape of CPB has little effect on its performance.

2.17.2 Thickness of the concrete pavement block

Knapton (1976) conducted a study to investigate the effect of CPB thickness on the structural performance of concrete pavement block. It was observed that the CPB thickness has either no effect or very small effect on pavement behaviour. However, accelerated trafficking tests have established that an increase in paving unit thickness is beneficial to pavement performance under traffic (Shackel, 1979a; Shackel, 1982). This is manifested as reduction in the permanent deformations and elastic deflections of the pavement and in the stresses transmitted to the sub-grade (Shackel, 1979a). It has been observed that changes in the thickness of CPB have a great effect on the performance of pavement than corresponding changes in the thickness of the base or sub-base.

2.17.3 Laying Pattern

The shapes of CPB influence its laying pattern. Shackel (1980b) conducted trafficking tests to compare the performance of CPBs installed in herringbone, stretcher, and basket weave bonds. Figure 2.4 shows examples of common laying patterns of CPBs.



Stretcher bond (least effective)

Basket-weave bond (less effective)

Herringbone bond (most effective, traffic direction not critical)

Figure 2.4: Common laying pattern of concrete pavement blocks (Ling, 2008)

Generally, pavements laid in herringbone bond are believed to provide the smallest traffic-associated deformations while the greatest deformations are associated with stretcher bond pattern. The benefits of herringbone pattern are even more pronounced where the pavement has to resist slewing or turning loads (Shackel, 1980a).It has been found that the orientation of the laying pattern with respect to the direction of trafficking has a small influence on performance when the CPBs are installed in herringbone pattern.

2.17.4 Strength of the individual concrete pavement block

Shackle (1979b) and Rollings (1982) reported that the compressive strength of the CPB unit has little influence on the response of CPB to traffic. Panda and Ghosh (2002a) conduct a test with three different strength levels. It was observed that the shape of the load deflection path was similar, and the deflection was almost the same for all CPB types. It was found that the individual CPB was subjected to compressive stress with negligible bending stress because of its small size. The elastic modulus of the CPB was many times higher than that of the underlying materials. The CPBs behave as rigid bodies in the pavement and transfer the external load by virtue of its geometrical characteristics, rather than its strength to the adjacent CPBs and underlying layers. It was established that load-associated performance of concrete pavements was not dependent on the compressive strength of the CPB, considered in the study.

2.17.5 Bedding sand

When concrete block pavement is subjected to truck traffic, a significant proportion of the initial deformation occurred in the bedding layer which had compacted thickness of 40 mm (Barber & Knapton, 1980). A similar result was reported by Seddon (1980). Shackel (1979a) also observed that a reduction in the loose of the bedding sand from 50 mm to 30 mm was beneficial to the deformation behaviour of concrete block pavements. It is generally agreed that the bedding sand layer in concrete block pavements should be as thin as practicably possibly.

2.17.6 Base

Studies show that most materials used as base course in flexible pavement can also be used successfully in concrete block pavements. Examples of such materials are crushed rocks, selected gravels, cement stabilized materials, lean concrete etc.

Comparisons of the performance under traffic of concrete block pavements laid on several type of base have been made (Shackel, 1980a; Shackel, 1980b; Shackel, 1982). For identical base and pavement thickness, the best levels of performance are usually achieved by using cement-treated materials, closely followed by the use of crushed rock (Shackel, 1980a; Shackel, 1980b; Shackel, 1982). Gravels and waste products such as blast furnace slags gave performance to crushed rocks, but the worst performance of all base materials has usually been associated with asphalt-treated material.

2.18 Summary

In this chapter, a review of material constituents of rubberized concrete has been extensively dealt with. The literature revealed that rubberized concrete is produced by partially or fully replacing the mineral aggregate in concrete with rubber. Mechanical grinding and cryogenic grinding are the two processing technologies used to convert scrap tyres into rubber aggregate.

It was established that the use of rubber as aggregate in concrete has significant effect on the physical and mechanical properties of rubberized concrete. The review shows that the replacement of natural aggregate with rubber aggregate tends to lower the density, compressive strength, and tensile strength of rubberized concrete. However, the flexural strength, toughness, impact resistance, and resilience of concrete tend to improved when rubber aggregate is used; depending on the volume of rubber that would be used to replace the natural aggregates. It was also observed that these properties of rubberized concrete improve when the surface texture of the rubber aggregate is treated.

Again, this chapter discussed the cost consideration of rubberized concrete. It was shown that recycled rubber aggregate for concrete are more expensive than the mineral aggregate to be replaced. However, the economics of using rubber in concrete is expected to change as the market potential of this product developed and the demand of recycled rubber is increased. This shows promise for the future commercial application of rubber in larger range of concrete products.

Furthermore, this chapter dealt with the material constituents of concrete pavement blocks. It was observed that the materials used for the production of concrete pavement blocks are not different from that of rubberized concrete. Methods of manufacturing concrete pavement blocks were also discussed. These methods are pressure only and high frequency vibration.

Finally, the nature of concrete pavement blocks and factors that affect the structural performance of concrete block pavement were extensively discussed. These factors include the shape and size of the concrete pavement block, thickness of the concrete pavement block, laying pattern, strength of the individual concrete pavement blocks, bedding sand, and the material used for the base.

CHAPTER THREE

LABORATORY EXPERIMENTAL STUDIES

3.0 Introduction

In this chapter, the various materials used for the studies are discussed. The procedures and methods used to collect the data for analysis are also described.

3.1 Materials

The materials used to develop the RCPBs in this study consist of Ordinary Portland cement (OPC), sand, quarry dust, coarse aggregate (stones), ground vehicular tyre (GVT), and water. Figure 3.1 shows samples of the cement, sand, quarry dust, stones, and GVT used to develop the RCPBs.

Figure 3.1: Samples of the materials used to develop the RCPBs

3.1.1 Cement

Ordinary Portland cement (CEM I 42.5 N) produced by Ghana cement works (Ghacem) that conformed to EN 197-1 and labelled OPC was used. The mean particle size (µm) and specific gravity of the OPC were 4 and 3.14 respectively. Table 3.1 shows the chemical composition of the OPC.

Table 3.1: Chemical composition of ordinary Portland cement (Bediako et al., 2010)

Chemical composition	Content (%)
Silicon dioxide (SiO_2)	19.70
Aluminium oxide (Al_2O_3)	5.00
Ferric oxide (Fe_2O_3)	3.16
Calcium oxide (CaO)	63.03
Magnesium oxide (MgO)	1.75
Potassium oxide (K_2O)	0.16
Sodium oxide (Na_2O)	0.20
Sulphur oxide (SO_3)	2.80
Loss on ignition (LOI)	2.58

3.1.2 Sand

Pit sand from Jacobu in the Ashanti Region of Ghana was used for the production of the RCPB. The maximum particle size of the sand was 2.36mm. The sand was dried in an opened place to remove the moisture.

3.1.3 Quarry dust

Quarry dust produced by Naachiaa Stones and Quarry Limited was used for the studies. The maximum particle size of the quarry dust was 2.36mm.

3.1.4 Coarse aggregate

Crushed granite produced by Naachiaa Stones and Quarry Limited was used as coarse aggregate. The maximum particle size of the coarse aggregate was 10mm.

3.1.5 Ground vehicular tyre

Ground vehicular tyre produced with the help of grind-stone machine was used for the experiment. The maximum particle size of the GVT was 1.18mm.

3.1.6 Water

Potable water produced by Jacobu water supply system was used for the preparation and curing of the RCPB specimens.

3.2 Experimental Procedures and Methods

3.2.1 Determination of sieve analysis of materials

3.2.1.1 Sand

The grading of the sand was done in accordance with ASTM C136. The sample of the sand was shaken through a series of wire-cloth sieves with square openings, nested one above the other in other of size with the sieve having the largest opening on top, the one having the smallest opening at the bottom, and a pan underneath to catch material passing the finest sieve. The weight retained in each sieve and in the pan was determined. The individual % retained was then calculated from the formula below:

$(Ws / Ts) \times 100$

Where Ws = weight of sample in sieve or pan

Ts = total weight of sample.

The cumulative % retained was determined by adding the various % retained for each sieve. Finally, the % passing for each sieve was calculated by subtracting its cumulative % retained from 100.

3.2.1.2 Quarry dust

The procedure is the same as the one described in Section 3.2.1.1 of this chapter.

3.2.1.3 Coarse aggregate

The procedure is the same as the one described in Section 3.2.1.1 of this chapter.

3.2.1.4 GVT

The procedure is the same as the one described in Section 3.2.1.1 of this chapter.

3.2.2 Determination of physical properties of materials

3.2.2.1 Sand

The following physical properties of the sand were determined:

Fineness modulus, compacted bulk density, specific gravity, particle density, moisture content, and silt content.

3.2.2.1.1 Fineness modulus of sand

Fineness modulus of the sand was calculated from the formula below:

FM = $\sum$cumulative % retained / 100, where FM is the fineness modulus.

3.2.2.1.2 Compacted bulk density of sand

Compacted bulk density of sand was done in accordance with BS 812: Part 2. A cylindrical container was used. The diameter of the container was first determined by taking the diameter from three different sizes and the average was calculated. The height was measured. The volume of the container was calculated from the formula:

$V = \Pi r^2 h$,

Where V = volume of the cylindrical container

r = radius of the container and

h = height of the container.

The container was then filled about one-third full with the sand. With the aid of metallic rod, twenty compactive blows were given to the sand from a height of about 50mm above its surface. Similar quantity of the sand was added and the same number of blows was given to it. The container was then filled to overflow and tamped again with the same number of blows. The surplus sand was removed by rolling the rod across the top of the container. The mass of the sand in the container was determined. The compacted bulk density of the sand was calculated from the formula below;

D = M / V,

Where D = the compacted bulk density of sand

M = mass of the sand in the container and

V = volume of the cylindrical container.

3.2.2.1.3 Specific gravity of sand

Specific gravity of sand was done in accordance with ASTM C128. Sample of the sand was dried to a constant mass at 100^0C, cooled in air, and immersed in water for 24 hours. The water was drained off from the sand and the sample was spread on a flat surface. The sand was then exposed to natural air dry. The sand was stirred until it reached its saturated surface-dry condition. 500g of the saturated surface-dry sand was placed in a glass flask, and water was added to it to fill its calibrated mark. The total mass of the flask, sand, and water was determined (Figure 3.2). The sand was carefully removed from the flask into a pan, oven-dried, and its mass was determined. Finally, the mass of the flask filled with water to its calibrated mark was determined. The specific gravity values of the sand were calculated from the formulae below:

Bulk specific gravity = A / (S + B – C) and Bulk specific gravity SSD = S / (S + B – C).

Where A = the mass of oven-dry sample in air

S = the mass of saturated surface-dry sample in air

B = the mass of flask filled with water and

C = the mass of flask with sand and water to the calibration or filling mark.

Figure 3.2: Taking the mass of flask filled with sand and water

3.2.2.1.4 Particle density of sand

The particle density of sand was calculated from the formula below:

Particle density = specific gravity of sand × density of water.

3.2.2.1.5 Moisture content test of sand

500g of the original sample was determined. The 500g sample was dried to a constant mass at 100^0C and cooled in air. The mass of the dried sample was then determined. The total moisture content was calculated from the formula below:

Total moisture content = $[(W - W_{OD}) / W_{OD}] \times 100$,

Where W = the mass of the original sample

W_{OD} = the mass of the dried sample.

3.2.2.1.6 Silt content test of the sand

Glass flask was filled half way with sample of the sand. Water was added to the sand to about 2/3 full of the flask. It was allowed to settle for a couple of days. The total height of the sand in the flask was measured. The height of the silt was also measured. The silt content of the sand was calculated from the formula below:

Silt content = $(H_s / H) \times 100$

Where Hs = height of silt in the soil

H = total height of soil in the flask.

3.2.2.2 Quarry dust

The following physical properties of quarry dust were determined:

Fineness modulus, compacted bulk density, specific gravity, particle density, and moisture content.

3.2.2.2.1 Fineness modulus of quarry dust

Fineness modulus of the quarry dust was calculated from the formula below;

FM = ∑ cumulative % retained / 100, where FM is the fineness modulus.

3.2.2.2.2 Compacted bulk density of quarry dust

The procedure is the same as the one described in Section 3.2.2.1.2 of this chapter.

3.2.2.2.3 Specific gravity of quarry dust

The procedure is the same as the one described in Section 3.2.2.1.3 of this chapter.

3.2.2.2.4 Particle density of quarry dust

The particle density of quarry dust was calculated from the formula below:

Particle density = specific gravity of quarry dust × density of water.

3.2.2.2.5 Moisture content of quarry dust

The procedure is the same as the one described in Section 3.2.2.1.5 of this chapter.

3.2.2.3 Coarse aggregate

The following physical properties of the coarse aggregate were determined: Fineness modulus, compacted bulk density, specific gravity, particle density, and moisture content.

3.2.2.3.1 Fineness modulus of coarse aggregate

Fineness modulus of the coarse aggregate was calculated from the formula below; FM = ∑cumulative % retained / 100, where FM is the fineness modulus.

3.2.2.3.2 Compacted bulk density of coarse aggregate

The procedure is the same as the one described in Section 3.2.2.1.2 of this chapter.

3.2.2.3.3 Specific gravity of coarse aggregate

Specific gravity of coarse aggregate was done in accordance with ASTM C127. Sample of the coarse aggregate was thoroughly washed, dried to constant mass at 100^0C, cooled in air, and immersed in water for 24 hours. It was then removed from the water and dried to a saturated surface dry state with a large absorbent cloth. 500g of the saturated surface-dry sample was then determined. The saturated surface-dry sample was put in flask containing water. The apparent mass of saturated sample in water was determined by subtracting the mass of the volume of water displaced from the mass of the saturated surface-dry sample in air. After the mass in water was determined the sample was oven-dried, and its oven-dry mass was determined. The bulk specific gravity and bulk specific gravity SSD was calculated from the formulae below:

Bulk specific gravity = A / (B – C) and Bulk specific gravity SSD = B / (B – C)

Where A = the mass of oven-dry sample in air

B = the mass of saturated surface-dry sample in air and

C = the apparent mass of saturated sample immersed in water.

3.2.2.3.4 Particle density of coarse aggregate

The particle density of coarse aggregate was calculated from the formula below:

Particle density = specific gravity of coarse aggregate × density of water.

3.2.2.3.5 Moisture content of coarse aggregate

The procedure is the same as the one described in Section 3.2.2.1.5 of this chapter.

3.2.2.4 Ground vehicular tyre (GVT)

The following physical properties of GVT were determined:

Fineness modulus, compacted bulk density, specific gravity, and particle density.

3.2.2.4.1 Fineness modulus of GVT

Fineness modulus of the GVT was calculated from the formula below;

FM = $\sum$cumulative % retained / 100, where FM is the fineness modulus.

3.2.2.4.2 Compacted bulk density of GVT

The procedure is the same as the one described in Section 3.2.2.1.2 of this chapter.

3.2.2.4.3 Specific gravity of GVT

Specific gravity of GVT was done in accordance with Florida method of test for testing of ground tyre rubber (designation: 5 – 559). A flask was filled with ethyl alcohol to a calibration mark. The weight of the flask with the alcohol was determined and recorded. The flask was then emptied. 50g of ground tyre sample was determined. The weighed tyre was put into the empty flask, and filled with alcohol to the calibration mark. The weight of flask with the tyre and alcohol was determined (Figure 3.3). Specific gravity of GVT was calculated from the formula below:

Specific gravity of GVT = [(0.9971 × Wa) x D] / [Wa – (Wb – Wc)]

Where Wa = Mass of original sample

Wb = Mass of flask filled with rubber and alcohol

Wc = Mass of flask filled with alcohol and

D = Density of alcohol.

Figure 3.3: Taking the mass of flask filled with rubber and alcohol

3.2.2.4.4 Particle density of GVT

The particle density of GVT was calculated from the formula below:

Particle density = specific gravity of GVT × density of ethyl alcohol.

3.2.3 Mix proportion for the RCPBs

The mix proportion was 1: 1: 2: 2.25 (cement: coarse aggregate: quarry dust: sand). Target strength of 30 $\underline{+}$ 5 N/mm^2 would be expected. The percentage weight of the GVT was 0%, 10%, 20%, 30%, 40%, 50%, and 60% by volume of sand.

3.2.4 Batching

Different water cement (W/C) ratios (0.20, 0.25, 0.30, and 0.35) were used for the experiment at the initial stage. The plain concrete was used as a control test and denoted as Aj, where j is the water cement ratio. The rest of the batches with GVT were denoted as Bi/j. Where B is the batch with certain % of GVT, i is the volume percentage of GVT and j is the W/C ratio. Each batch was used to prepare 8 specimens. Later, the optimum W/C ratio (0.35) was used to prepare additional specimens.

3.2.5 Computation of mass of constituent materials for the specimens

Size of mould: length = 200mm, breath = 100mm, and depth = 60mm.

Volume of specimen = $0.20 \times 0.10 \times 0.06$

$= 1.2 \times 10^{-3}$ m^3

Volume of 8 specimens = $8 \times 1.2 \times 10^{-3}$

$= 9.6 \times 10^{-3}$ m^3

Taking unit weight of concrete = 24 KN/m^3

Weight of 8 specimens = $24 \times 9.6 \times 10^{-3}$

= 0.2304 KN

= 230.4 N

Force = mass × acceleration due to gravity.

Taking acceleration due to gravity = $9.81ms^{-2}$

Mass of 8 specimens = 230.4 / 9.81

= 23kg

Add 10% wastage and compaction = (110 / 100) × 23

Required mass of 8 specimens = 25 kg

Using mix proportions, the mass of each constituent material required was given in Table 3.2.

Table 3.2: Quantity of materials for the mix ratio

	Constituents of RCPBs (weight in Kg)					
Batch	Water	Cement	Stones	Quarry dust	sand	GVT
A 0.20	0.8	4	4	8	9.0	0.000
A 0.25	1.0	4	4	8	9.0	0.000
A 0.30	1.2	4	4	8	9.0	0.000
A 0.35	1.4	4	4	8	9.0	0.000
B10 / 0.20	0.8	4	4	8	8.1	0.243
B10 / 0.25	1.0	4	4	8	8.1	0.243
B10 / 0.30	1.2	4	4	8	8.1	0.243
B10 / 0.35	1.4	4	4	8	8.1	0.243
B20 / 0.20	0.8	4	4	8	7.2	0.486
B20 / 0.25	1.0	4	4	8	7.2	0.486
B20/ 0.30	1.2	4	4	8	7.2	0.486
B20 / 0.35	1.4	4	4	8	7.2	0.486
B30 / 0.20	0.8	4	4	8	6.3	0.729
B30 / 0.25	1.0	4	4	8	6.3	0.729
B30 / 0.30	1.2	4	4	8	6.3	0.729
B30 / 0.35	1.4	4	4	8	6.3	0.729
B40 / 0.20	0.8	4	4	8	5.4	0.972
B40 / 0.25	1.0	4	4	8	5.4	0.972
B40 / 0.30	1.2	4	4	8	5.4	0.972
B40 / 0.35	1.4	4	4	8	5.4	0.972
B50 / 0.20	0.8	4	4	8	4.5	1.215
B50 / 0.25	1.0	4	4	8	4.5	1.215
B50 / 0.30	1.2	4	4	8	4.5	1.215
B50 / 0.35	1.4	4	4	8	4.5	1.215
B60 / 0.20	0.8	4	4	8	3.6	1.458
B60 / 0.25	1.0	4	4	8	3.6	1.458
B60 / 0.30	1.2	4	4	8	3.6	1.458
B60 / 0.35	1.4	4	4	8	3.6	1.458

* Density of sand = 1697 Kg/m^3 and density of GVT = 463 Kg/m^3. Therefore, weight of GVT for an equivalent volume of sand (conversion factor) = 463/1697

= 0.27

3.2.6 Preparation of RCPBs

The sand, cement, quarry dust, and GVT were weighed and put in a plastic container. They were mixed thoroughly by hand using trowel until a uniformed grey colour was obtained .The coarse aggregate was then added to it and mixed for further 5 minutes. Water was then added and mixed continuously until uniformity was apparent. Steel mould with internal dimensions of 200mm in length, 100mm in width, and 60mm in depth was used to mould the RCPBs. The mix was poured into oiled mould, compactions were applied manually by using a hammer and wooden stem. The RCPBs were then removed carefully from the steel mould. The mould was then oiled and the process continued until the required number of RCPBs was obtained. The prepared RCPBs were packed on boards for 24 hours before curing started. Figure 3.4 demonstrates the preparation processes of the RCPBs.

Mixing of materials

Compaction of RCPB

Removal of mould from RCPB

Figure 3.4: Preparation of RCPBs

3.2.7 Curing of RCPBs

The RCPBs were cured under a shed. They were covered with wet cotton sacks. Water was poured on them twice in every day. This was done in order to prevent excessive evaporation of water from the RCPBs. Figure 3.5 shows samples of the RCPBs after curing.

Figure 3.5: Sample of the RCPBs after curing.

3.2.8 Testing of specimens

A range of tests were carried out in the Structure and Material Laboratory at Department of Building Technology, Sunyani Polytechnic to determine the density, compressive strength, water absorption, flexural strength, and splitting tensile strength of the RCPBs. The compressive strength, flexural strength, and splitting tensile strength were tested at 7 days, 14 days, and 28 days curing age while the density and water absorption were tested at only 28 days curing age. For all the tests conducted, 5 specimens were tested for each batch.

3.2.8.1 Density

According to BS 1881 part 114 (1983), density is the mass of a unit volume of hardened concrete expressed in kilograms per cubic metre. Determinations of the masses of the specimens are shown in Figure 3.6. The densities of the RCPBs were therefore calculated by dividing weight (kg) by the dimensions of the blocks (m^3).

Density = M/V

Where M = mass of specimen (kg) and

V = volume of specimen calculated from dimensions (m^3).

Figure 3.6: Weighing of RCPB

3.2.8.2 Compressive strength

The test consists of a specimen being axially loaded by a compressive force until failure of the specimen is observed. Compressor machine with maximum capacity of 2000 KN and compaction rate of 200kg Pascal per second was used to determine the compressive strength of the RCPBs. Figure 3.7 shows the set-up of the test. The compressive strength was calculated in accordance with BS 6717: Part 1 (1986). The compressive strength was calculated from the formula below:

$C_s = P / A$

Where C_s = compressive strength (N/mm^2)

P = the ultimate load at failure (N) and

A = the area perpendicular to the applied load (mm^2)

Figure 3.7: Set up of the compressive strength test

3.2.8.3 Water absorption

The water absorption was tested in accordance with ASTM C642 (2006). The masses of the specimens were initially determined. The specimens were then immersed in water for 24 hours (Figure 3.8), removed and weighed again. Water absorption was calculated from the formula below;

Water absorption (%) = $[(M_2 – M1) / M_1] \times 100$

Where M_1 = mass of specimen before immersion and

M_2 = mass of specimen after immersion.

Figure 3.8: Immersion of specimens into tank containing water

3.2.8.4 Flexural strength

Universal testing machine was used for the test. A centre line was marked at the top of the specimen, using a red marker perpendicular to its length. The RCPBs were tested under the centre line load while simply supported over supporting span of 150 mm (BSI, 2001). Figure 3.9 shows the test set up. The flexural strength was calculated from the formula below,

$$\text{Flexural strength} = \frac{3}{2}\frac{LF}{BD^2}$$

Where L = the span length (mm)

F = the maximum load applied (N)

B = the width of the sample (mm)

D = the thickness of the sample (mm)

Figure 3.9: Set up of the flexural strength test

3.2.8.5 Splitting tensile strength

Universal testing machine was used for the test. The test involves applying a line loads to the top and bottom of the block using two steel bars (BSI, 2001). Plywood strips are inserted between the bars and the blocks to ensure an even load distribution. The set-up of the test is shown in Figure 3.10. Upon failure, the maximum applied load was recorded and the splitting tensile strength (T) was calculated from the formula below,

$$T = \frac{0.868 \times K \times F}{(L \times D)}$$

Where T = splitting tensile strength (N/mm^2)

F = Load at failure (N)

L = length of the specimen (mm)

D = thickness of the specimen (mm)

K = correction factor for thickness, calculated from the equation,

$K = 1.3 – 30 (0.18 – t/1000)^2$, t is the thickness of specimen.

Figure 3.10: Set up of the splitting tensile strength test

3.3 Data Analysis

The data were analysed with the aid of descriptive statistics and statistical tools like two factor independent measures analysis of variance (ANOVA), Pearson correlation, and multiple regression analysis. For all the statistical tools, the significance level of $p<.05$ was used to assess the significant effect the independent variable has on the dependent variable.

CHAPTER FOUR

RESULTS

4.0 Introduction

This chapter presents the results of the physical properties of the materials used for the preparation of the RCPBs. The results of the sieve analysis conducted on the various materials are also reported. Finally, the results of the various test carried out in line with the objectives of this study are reported.

4.1 Physical Properties and Sieve Analysis of Sand

4.1.1 Physical properties of sand

Table 4.1 shows the physical properties of the sand used for the study. The fineness modulus, compacted bulk density, bulk specific gravity, bulk specific gravity SSD, particle density, moisture content, and silt content are 2.50, 1697 kg/m^3, 2.60, 2.71, 2.60g/cm^3, 1.94%, and 2.85% respectively.

Table 4.1: Physical properties of sand

Property	Test result
Fineness modulus	2.50
Compacted bulk density	1697kg/m^3
Bulk specific gravity	2.60
Bulk specific gravity SSD	2.71
Particle density	2.60g/cm^3
Moisture content	1.94%
Silt content	2.85%

4.1.2 Sieve analysis of sand

Table 4.2 shows the results of the sieve analysis of the sand. The table demonstrates that greater percentage (27.24%) of the particle sizes of the sand was retained by 0.60 mm sieve. However, 8.29% of the particles passed through the 0.15 mm sieve. The sieve analysis also displays that the sand used for the study conformed to zone II as per IS: 383 – 1970. The graph of % passing of sand and sieve size is shown in Figure 4.1.

Table 4.2: Sieve analysis of sand

IS sieve size (mm)	Weight retained	% retained	Cumulative % retained	% passing	Lower limit	Upper limit
10.00	0	0.00	0.00	100.00	100	100
4.75	0	0.00	0.00	100.00	90	100
2.36	46	3.89	3.89	96.11	75	100
1.18	258	21.83	25.72	74.28	55	90
0.60	322	27.24	52.96	47.04	35	59
0.30	274	23.18	76.14	23.86	8	30
0.15	184	15.57	91.71	8.29	0	10
Pan	98	8.29				

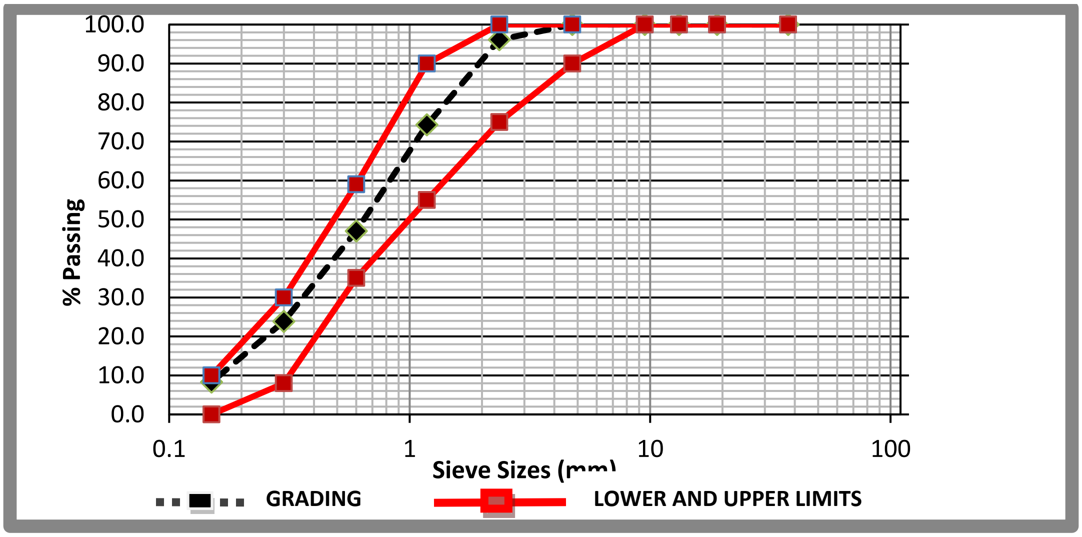


Figure 4.1: Graph of % passing of sand and sieve sizes (mm).

4.2 Physical Properties and Sieve Analysis of Quarry Dust

4.2.1 Physical properties of quarry dust

Table 4.3 displays the physical properties of the quarry dust used for the study. The fineness modulus, compacted bulk density, bulk specific gravity, bulk specific gravity SSD, particle density, and moisture content are 3.11, 1697kg/m^3, 2.60, 2.72, 2.60g/cm^3, and 1.83% respectively.

Table 4.3: Physical properties of quarry dust

Property	Test result
Fineness modulus	3.11
Compacted bulk density	1697kg/m3
Bulk specific gravity	2.60
Bulk specific gravity SSD	2.72
Particle density	2.60g/cm3
Moisture content	1.83%

4.2.2 Sieve analysis of quarry dust

The result of the sieve analysis of the quarry dust is shown in Table 4.4. The table demonstrates that greater percentage (27.65%) of the particle sizes of the quarry dust was retained by 1.18 mm sieve. However, 8.04% of the particles passed through the 0.15 mm sieve. The analysis displays that the quarry dust used for the study conformed to zone I as per IS: 383 – 1970. The graph of % passing of quarry dust and sieve size is shown in Figure 4.2.

Table 4.4: Sieve analysis of quarry dust

IS sieve size (mm)	Weight retained	% retained	Cumulative % retained	% passing	Lower limit	Upper limit
10.00	0	0.00	0.00	100.00	100	100
4.75	0	0.00	0.00	100.00	90	100
2.36	167	20.34	20.34	79.66	60	95
1.18	227	27.65	47.99	52.01	30	70
0.60	170	20.71	68.70	31.30	15	34
0.30	110	13.40	82.10	17.90	5	20
0.15	81	9.86	91.96	8.04	0	10
Pan	66	8.04				

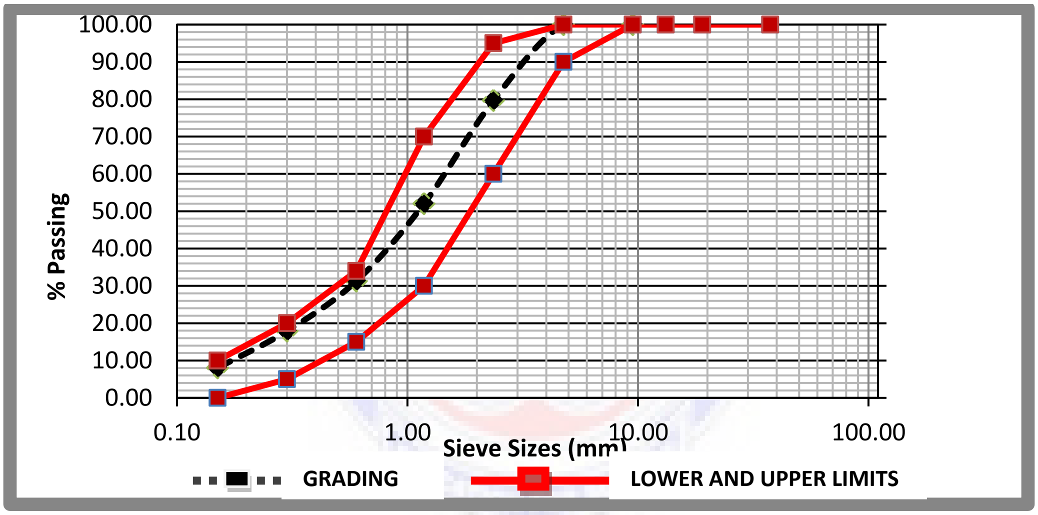


Figure 4.2: Graph of % passing of quarry dust and sieve sizes (mm)

4.3 Physical Properties and Sieve Analysis of Coarse Aggregate

4.3.1 Physical properties of coarse aggregate

Physical properties of coarse aggregate used for the study are shown in Table 4.5. The fineness modulus, compacted bulk density, bulk specific gravity, bulk specific gravity SSD, particle density, and moisture content are 1.97, 1722kg/m^3, 2.75, 2.84, 2.75g/cm^3 and 1.38 respectively.

Table 4.5: Physical properties of coarse aggregate

Property	Test result
Fineness modulus	1.97
Compacted bulk density	1722Kg/m^3
Bulk specific gravity	2.75
Bulk specific gravity SSD	2.84
Particle density	2.75g/cm^3
Moisture content	1.38

4.3.2 Sieve analysis of coarse aggregate

Table 4.6 exhibits the results of the sieve analysis of the coarse aggregate. The table demonstrates that greater percentage (80.16%) of the particle sizes of the coarse aggregate was retained by 4.75 mm sieve. However, 0.08% of the particles passed through the 0.15 mm sieve. The analysis shows that the grading limit of the 10 mm coarse aggregate used for the study conformed to IS: 383 – 1970. The graph of % passing of coarse aggregate and sieve size is shown in Figure 4.3.

Table 4.6: Sieve analysis of coarse aggregate

IS sieve size (mm)	Weight retained	% retained	Cumulative % retained	% passing	Lower limit	Upper limit
12.5	0	0.00	0	100.00	100	100
10	106	8.58	8.58	91.42	85	100
4.75	990	80.16	88.74	11.26	0	20
2.36	138	11.18	99.92	0.08	0	5
Pan	1	0.08				

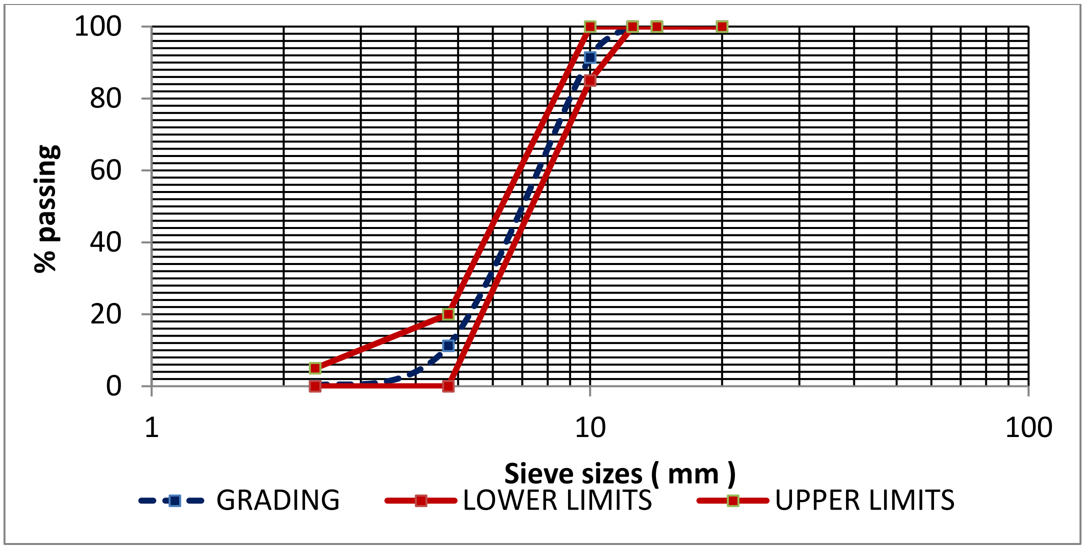


Figure 4.3: Graph of % passing of coarse aggregate and sieve sizes (mm).

4.4 Physical Properties and Sieve Analysis of GVT

4.4.1 Physical properties of GVT

Physical properties of the GVT used for the study are displayed in Table 4.7. The fineness modulus, compacted bulk density, specific gravity, and particle density are 1.31, 463kg/m^3, 1.12 and 0.9g/cm^3 respectively.

Table 4.7: Physical properties of GVT

Property	Test result
Fineness modulus	1.31
Compacted bulk density	463kg/m^3
specific gravity	1.12
Particle density	0.9g/cm^3

4.4.2 Sieve analysis of GVT

Table 4.8 shows the results of the sieve analysis of the GVT. The table demonstrates that greater percentage (22.51%) of the particle sizes of the GVT was retained by 0.15 mm sieve. However, 37.70% of the particles passed through the 0.15 mm sieve.

Table 4.8: Sieve analysis of GVT

IS sieve size (mm)	Weight retained	% retained	Cumulative % retained	% passing
10.00	0	0.00	0.00	100
4.75	0	0.00	0.00	100
2.36	0	0.00	0.00	100
1.18	12	6.28	6.28	93.72
0.60	31	16.23	22.51	77.49
0.30	33	17.28	39.79	60.21
0.15	43	22.51	62.30	37.70
Pan	72	37.70		

4.5 Physical Properties of RCPBs

4.5.1 Density

4.5.1.1 Effect of W/C ratio and GVT

Table 4.9 shows the results of density for the various batches used in the experiment. It can be observed that the density of RCPB increases as the W/C ratio increases. The density increased from 2125.31kg/m^3 to 2259.35kg/m^3, 2116.60kg/m^3 to 2184.70kg/m^3, 2047.61kg/m^3 to 2115.72kg/m^3, 1978.63kg/m^3 to 2046.74kg/m^3, 1909.65kg/m^3 to 1977.76kg/m^3, 1840.67kg/m^3 to 1908.78kg/m^3, and 1771.69kg/m^3 to 1839.80kg/m^3 at 0%, 10%, 20%, 30%, 40%, 50%, and 60% GVT content respectively. This means that the density was increased by about 3.5% when W/C ratio of 0.35 was used irrespective of the rubber content used.

It can also be noticed from Table 4.9 that the density decreases as the rubber content increases. The density reduction pattern is similar for the four different W/C ratios. The density decreased from 2125.31kg/m^3 to 1771.69kg/m^3, 2180.90kg/m^3 to

1794.39kg/m^3, 2250.10kg/m^3 to 1817.10kg/m^3, and 2259.35kg/m^3 to 1839.80kg/m^3 at 0.20, 0.25, 0.30, and 0.35 W/C ratios respectively. This indicates that the density was reduced by about 18% when 60% of the total sand was replaced by rubber regardless of the W/C ratio used.

A two factor independent measures analysis of variance at 0.05 significance level was conducted to determine whether GVT content and W/C ratio have significant effect on density of RCPBs (Table 4.10). It was also used to determine whether there was significant interaction between GVT content and W/C ratio. It was found that the effect of GVT content on density of RCPBs was statistically significant F(6,56) = 892100, P < 0.001. It was also found that the effect of W/C ratio on density was statistically significant F(3,56) = 848830, P < 0.001. The interaction between GVT content and W/C ratio was statistically significant F(18,56) = 1902, P < 0.001.

Table 4.9: Effect of W/C ratio and GVT content on density

	GVT content (%)						
W/C ratio	0	10	20	30	40	50	60
0.20	2125.30 Kg/m^3	2116.60 Kg/m^3	2047.61 Kg/m^3	1978.63 Kg/m^3	1909.65 Kg/m^3	1840.67 Kg/m^3	1771.69 Kg/m^3
0.25	2180.90 Kg/m^3	2139.29 Kg/m^3	2070.32 Kg/m^3	2001.33 Kg/m^3	1932.35 Kg/m^3	1863.37 Kg/m^3	1794.39 Kg/m^3
0.30	2250.10 Kg/m^3	2162.00 Kg/m^3	2093.02 Kg/m^3	2024.04 Kg/m^3	1955.05 Kg/m^3	1886.07 Kg/m^3	1817.10 Kg/m^3
0.35	2259.35 Kg/m^3	2184.70 Kg/m^3	2115.72 Kg/m^3	2046.74 Kg/m^3	1977.76 Kg/m^3	1908.78 Kg/m^3	1839.80 Kg/m^3

*Numbers with units represent the mean density of the various W/C ratios and GVT content

Table 4.10: Test of between subjects effects table showing the statistical significance of W/C ratio and GVT content on density of RCPBs

Dependent Variable: density

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	1.605E6[a]	27	59457.228	2.089E5	.000
Intercept	3.395E8	1	3.395E8	1.193E9	.000
Water cement ratio	72417.128	3	24139.043	8.483E4	.000
GVT content	1523186.019	6	253864.336	8.921E5	.000
Water cement ratio * GVT content	9742.020	18	541.223	1.902E3	.000
Error	15.935	56	.285		
Total	3.411E8	84			
Corrected Total	1605361.103	83			

a. R Squared = .987 (Adjusted R Squared = .981)

4.5.2 Water absorption

The results of water absorption for the RCPBs are displayed in Table 4.11. It can be observed that the water absorption increases as the rubber content increases. The water absorption increased from 1.44% to 1.76%, indicating an increase of about 22% when 60% of the total sand was substituted with GVT.

Table 4.11: Result of water absorption

Batch	W/C ratio	Rubber content (%)	Water absorption (%)	% increase
A0.35	0.35	0	1.44	0.00
B10/0.35	0.35	10	1.50	4.17
B20/0.35	0.35	20	1.55	7.64
B30/0.35	0.35	30	1.59	10.42
B40/0.35	0.35	40	1.64	13.89
B50/0.35	0.35	50	1.70	18.06
B60/0.35	0.35	60	1.76	22.22

4.6 Mechanical Properties of RCPBs

4.6.1 Compressive strength

4.6.1.1 Effect of W/C ratio and GVT

Table 4.12 shows the results of compressive strength for the different W/C ratios and GVT contents used in the experiment. It can be noticed that the compressive strength increases as the W/C ratio increases. The compressive strength increased from 17.30N/mm^2 to 30.20N/mm^2, 14.39N/mm^2 to 25.10N/mm^2, 11.18N/mm^2 to 19.50N/mm^2, 9.11N/mm^2 to 15.90N/mm^2, 6.10N/mm^2 to 10.60N/mm^2, 3.63N/mm^2 to 6.30N/mm^2, and 2.48N/mm^2 to 4.30N/mm^2 at 0%, 10%, 20%, 30%, 40%, 50%, and 60% GVT content respectively. This indicates that the compressive strength was raised about 42% when W/C ratio of 0.35 was used regardless of the GVT content used.

It can also be observed that the compressive strength decreases as the GVT content increases (Table 4.12). The decrease pattern of the compressive strength is similar for the four different W/C ratios. The compressive strength reduced from 17.30N/mm^2 to 2.48N/mm^2, 22.40N/mm^2 to 3.20N/mm^2, 26.10N/mm^2 to 3.70N/mm^2, and 30.20N/mm^2 to 4.30N/mm^2 at 0.20, 0.25, 0.30, and 0.35 W/C ratios respectively. This shows that the compressive strength was decreased by about 86% when 60% of the total sand was substituted with rubber regardless of the W/C ratio used.

A two factor independent measures analysis of variance at 0.05 significance level was conducted to determine whether GVT content and W/C ratio have significant effect on compressive strength of RCPBs (Table 4.13). It was also used to determine whether there was significant interaction between GVT content and W/C ratio. It was found that the effect of GVT content on compressive strength of RCPBs was statistically significant $F(6,56) = 2572$, $P < 0.001$. It was also found that the effect of W/C ratio on compressive strength was statistically significant F(3,56) = 645.177, $P < 0.001$. The interaction between GVT content and W/C ratio was statistically significant F(18,56) = 1902, $P < 0.001$.

Table 4.12: Effect of W/C ratio and GVT content on compressive strength

W/C ratio	GVT content (%)						
	0	10	20	30	40	50	60
0.20	17.30 N/mm^2	14.39 N/mm^2	11.18 N/mm^2	9.11 N/mm^2	6.10 N/mm^2	3.63 N/mm^2	2.48 N/mm^2
0.25	22.40 N/mm^2	18.62 N/mm^2	14.47 N/mm^2	11.79 N/mm^2	7.89 N/mm^2	4.69 N/mm^2	3.20 N/mm^2
0.30	26.10 N/mm^2	21.62 N/mm^2	16.85 N/mm^2	13.74 N/mm^2	9.16 N/mm^2	5.44 N/mm^2	3.70 N/mm^2
0.35	30.20 N/mm^2	25.10 N/mm^2	19.50 N/mm^2	15.90 N/mm^2	10.60 N/mm^2	6.30 N/mm^2	4.30 N/mm^2

*Numbers with units represent the mean compressive strength of the various W/C ratios and GVT content

Table 4.13: Test of between subjects effects table showing the statistical significance of W/C ratio and GVT content on compressive strength of RCPBs

Dependent Variable: compressive strength

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	4908.661[a]	27	181.802	665.838	.000
Intercept	13560.555	1	13560.555	4.966E4	.000
Water cement ratio	528.483	3	176.161	645.177	.000
GVT content	4214.275	6	702.379	2.572E3	.000
Water cement ratio * GVT content	165.903	18	9.217	33.756	.000
Error	15.290	56	.273		
Total	18484.506	84			
Corrected Total	4923.951	83			

a. R Squared = .997 (Adjusted R Squared = .995)

4.6.1.2 Effect of curing age

Compressive strength results for 7 days, 14 days, and 28 days curing age are demonstrated in Figure 4.4. The compressive strength increases as the curing age increases regardless of the GVT content used. The compressive strength increased from 22.65N/mm^2 to 30.20N/mm^2, 18.57N/mm^2 to 25.10N/mm^2, 14.23N/mm^2 to 19.50N/mm^2, 11.92N/mm^2 to 15.90N/mm^2, 7.84N/mm^2 to 10.60N/mm^2, 4.60N/mm^2 to 6.30N/mm^2, and 3.17N/mm^2 to 4.30N/mm^2 at 0%, 10%, 20%, 30%, 40%, 50%, and 60% GVT content respectively. This suggests that the compressive strength was increased by about 26% when the curing age moved from 7 days to 28 days irrespective of the GVT content used.

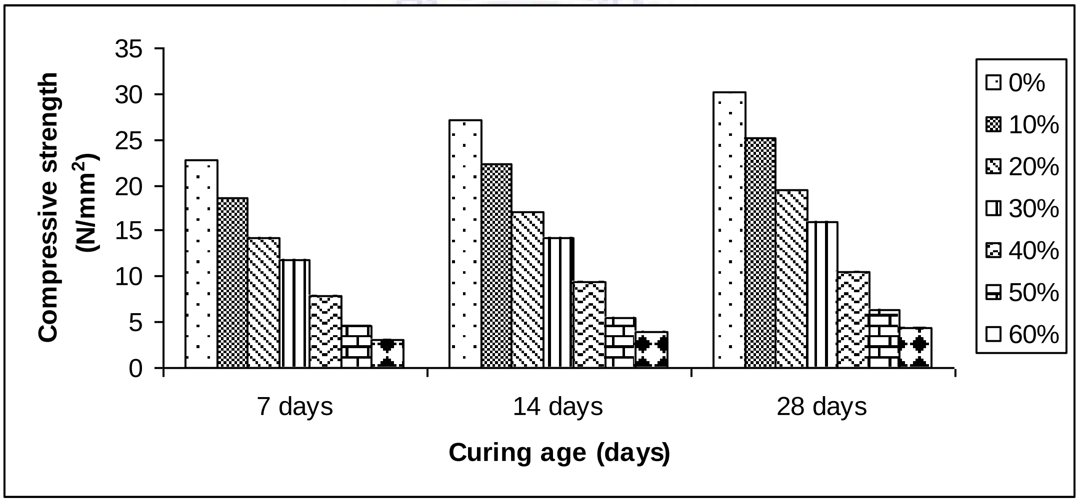


Figure 4.4: Compressive strength of different curing ages for W/C ratio of 0.35

4.6.2 Flexural strength

4.6.2.1 Effect of GVT

The test results of flexural strength for different GVT contents are shown in Table 4.14. It can be observed that as the rubber content increases the flexural strength decreases. The flexural strength decreased from 4.18N/mm^2 to 1.28 N/mm^2, indicating a reduction of about 69% when 60% volume of the sand was replaced with GVT.

Table 4.14: 28 day Flexural strength test results

Batch	W/C ratio	Rubber content (%)	Flexural strength (N/mm^2)	% loss in strength
A0.35	0.35	0	4.18	0.00
B10/0.35	0.35	10	3.81	8.85
B20/0.35	0.35	20	3.35	19.86
B30/0.35	0.35	30	2.86	31.58
B40/0.35	0.35	40	2.21	47.13
B50/0.35	0.35	50	1.71	59.09
B60/0.35	0.35	60	1.28	69.14

4.6.2.2 Effect of curing age

Flexural strength results for 7 days, 14 days, and 28 days curing age are exhibited in Figure 4.5. It can be realised that flexural strength increases as the curing age increases irrespective of the GVT content used. The flexural strength increased from 3.13N/mm^2 to 4.18N/mm^2, 2.84N/mm^2 to 3.81N/mm^2, 2.49N/mm^2 to 3.35N/mm^2, 2.12N/mm^2 to 2.86N/mm^2, 1.64N/mm^2 to 2.21N/mm^2, 1.28N/mm^2 to 1.71N/mm^2, and 0.94N/mm^2 to 1.28N/mm^2 at 0%, 10%, 20%, 30%, 40%, 50%, and 60% GVT content respectively. This implies that the flexural strength was increased by about 25% when the curing age moved from 7 days to 28 days regardless of the GVT content used.

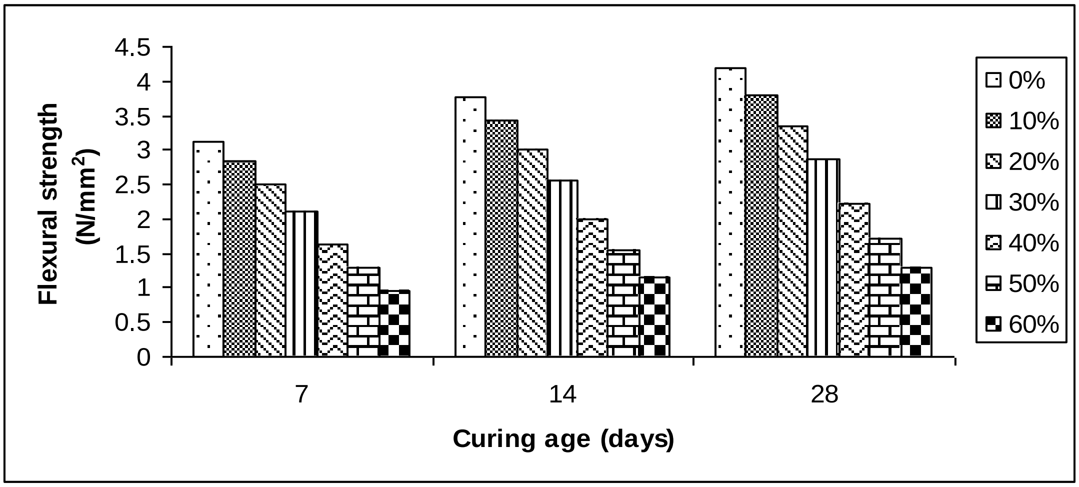


Figure 4.5: Flexural strength of different curing ages for W/C ratio of 0.35

4.6.3 Splitting tensile strength

4.6.3.1 Effect of GVT

The test results of splitting tensile strength for different GVT content are shown in Table 4.15. It can be observed that as the rubber content increases the splitting tensile strength decreases. The splitting tensile strength decreased from 3.92N/mm^2 to 0.97 N/mm^2, indicating a reduction of about 75% when 60% volume of the sand was replaced with GVT.

Table 4.15: 28 day splitting tensile strength test results

Batch	W/C ratio	Rubber content (%)	Splitting tensile strength (N/mm^2)	% loss in strength
A0.35	0.35	0	3.92	0.00
B10/0.35	0.35	10	3.67	6.38
B20/0.35	0.35	20	3.06	21.94
B30/0.35	0.35	30	2.56	34.69
B40/0.35	0.35	40	1.98	49.49
B50/0.35	0.35	50	1.29	67.09
B60/0.35	0.35	60	0.97	75.26

4.6.3.2 Effect of curing age

Splitting tensile strength results for 7 days, 14 days, and 28 days curing age are shown in Figure 4.6. It can be realised that splitting tensile strength increases as the curing age increases irrespective of the GVT content used. The splitting tensile strength increased from 2.85N/mm^2 to 3.92N/mm^2, 2.61N/mm^2 to 3.67N/mm^2, 2.30N/mm^2 to 3.06N/mm^2, 1.83N/mm^2 to 2.56N/mm^2, 1.45N/mm^2 to 1.98N/mm^2, 0.91N/mm^2 to 1.29N/mm^2, and 0.73N/mm^2 to 0.97N/mm^2 at 0%, 10%, 20%, 30%, 40%, 50%, and 60% GVT content respectively. This implies that the splitting tensile strength was increased by about 26% when the curing age moved from 7 days to 28 days regardless of the GVT content used.

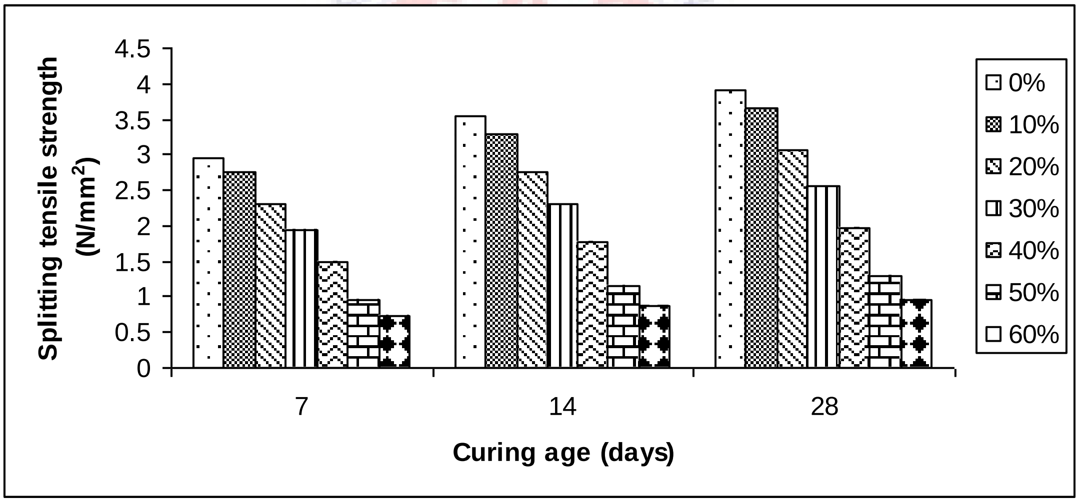


Figure 4.6: Splitting tensile strength of different curing ages for W/C ratio of 0.35

4.7 Relationship between Properties of Rubberized Concrete Pavement Blocks

4.7.1 Density and compressive strength

Figure 4.7 shows the relationship between density and compressive strength of RCPBs. It can be observed that there is a linear correlation between density and compressive strength. The coefficient of determination (R^2) was found to be 0.9904. The $R^2 = 0.9904$ indicates that 99.04% of the variation in compressive strength can be explained by the density of the RCPB. It can also be noticed that compressive strength (Cs) = - 114.59 + 0.0638d. The – 114.59 is the constant value for determining the compressive strength of the RCPBs. The 0.0638 means if density (d) is increased by one unit compressive strength will on average increase by 0.0638. A Pearson correlation was conducted to determine whether the correlation is statistically significant. It was found that $r = 0.995$ and $P < 0.001$ (Table 4.16). Positive value of 'r' indicates that as density increases, compressive strength increases. $P < 0.001$ shows that the correlation is statistically significant.

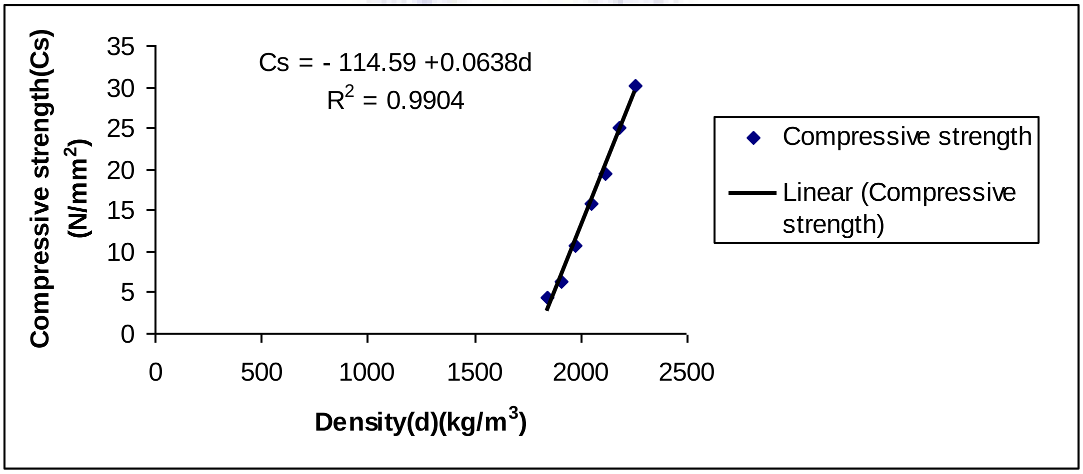


Figure 4.7: Relationship between density and compressive strength

Table 4.16: Pearson correlation showing the statistical significance of the correlation between density and compressive strength

		Density	Compressive strength
Density	Pearson Correlation	1	.995**
	Sig. (1-tailed)		.000
	N	7	7
Compressive strength	Pearson Correlation	.995**	1
	Sig. (1-tailed)	.000	
	N	7	7

**. Correlation is significant at the 0.01 level (1-tailed).

4.7.2 Compressive strength and flexural strength

Figure 4.8 displays the relationship between compressive strength and flexural strength of the RCPBs. It can be noticed that there is a linear correlation between compressive strength and flexural strength. The $R^2 = 0.984$ indicates that 98.4% of the variation in flexural strength can be explained by the compressive strength of the RCPB. It can also be observed that flexural strength (Fs) = 0.9845 + 0.1118Cs. The 0.9845 is the constant value for determining the flexural strength of the RCPBs. The 0.1118 means if compressive strength (Cs) is increased by one unit flexural strength will on average increase by 0.1118. A Pearson correlation was conducted to determine whether the correlation is statistically significant. It was found that $r = 0.992$ and $P < 0.001$ (Table 4.17). Positive value of ‘r’ indicates that as compressive strength increases, flexural strength increases. $P < 0.001$ shows that the correlation is statistically significant.

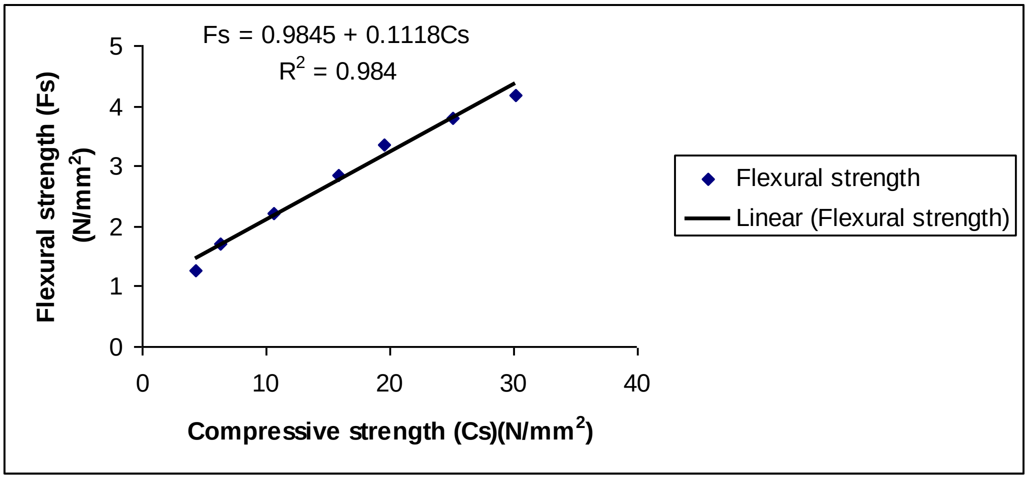


Figure 4.8: Relationship between compressive strength and flexural strength

Table 4.17: Pearson correlation showing the statistical significance of the correlation between compressive strength and flexural strength

		Compressive strength	Flexural strength
Compressive strength	Pearson Correlation	1	.992**
	Sig. (1-tailed)		.000
	N	7	7
Flexural strength	Pearson Correlation	.992**	1
	Sig. (1-tailed)	.000	
	N	7	7

**. Correlation is significant at the 0.01 level (1-tailed).

4.7.3 Compressive strength and splitting tensile strength

Figure 4.9 shows the relationship between compressive strength and splitting tensile strength of RCPBs. It can be observed that there is a positive correlation between compressive strength and splitting tensile strength. The $R^2 = 0.9819$ indicates that 98.19% of the variation in splitting tensile strength can be explained by the compressive strength of the RCPB. It can also be noticed that splitting tensile strength (T) = 0.6208 +

0.1171Cs. The 0.6208 is the constant value for determining the splitting tensile strength of the RCPBs. The 0.1171 means if compressive strength (Cs) is increased by one unit splitting tensile strength will on average increase by 0.1171. A Pearson correlation was conducted to determine whether the correlation is statistically significant. It was found that $r = 0.991$ and $P < 0.001$ (Table 4.18). Positive value of ‘r’ indicates that as compressive strength increases, splitting tensile strength increases. $P < 0.001$ shows that the correlation is statistically significant.

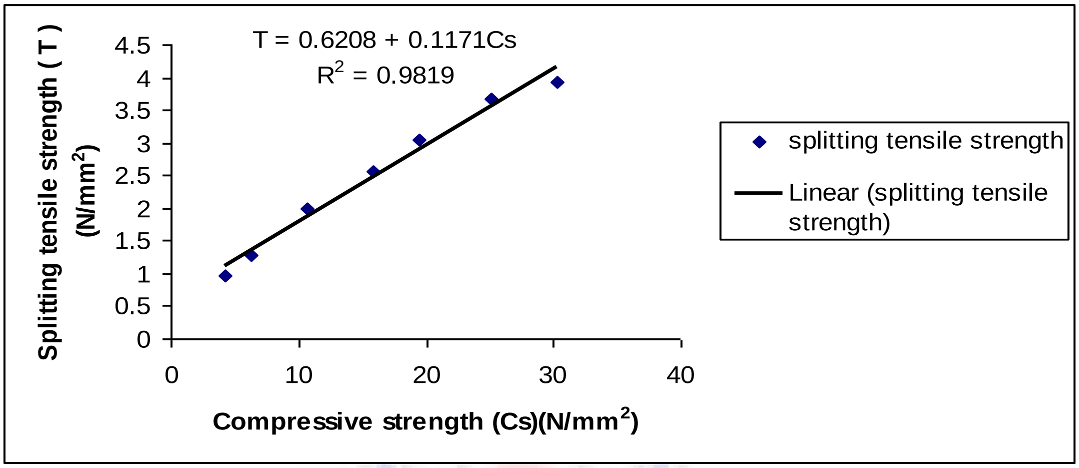


Figure 4.9: Relationship between compressive strength and splitting tensile strength

Table 4.18: Pearson correlation showing the statistical significance of the correlation between compressive strength and splitting tensile strength

		Compressive strength	Splitting tensile strength
Compressive strength	Pearson Correlation	1	.991**
	Sig. (1-tailed)		.000
	N	7	7
Splitting tensile strength	Pearson Correlation	.991**	1
	Sig. (1-tailed)	.000	
	N	7	7

**. Correlation is significant at the 0.01 level (1-tailed).

4.7.4 Flexural strength and splitting tensile strength

Figure 4.10 shows the relationship between flexural strength and splitting tensile strength of RCPBs. It can be seen that there is a linear correlation between flexural strength and splitting tensile strength. The $R^2 = 0.9964$ indicates that 99.64% of the variation in splitting tensile strength can be explained by the flexural strength of the RCPB. It can also be observed that splitting tensile strength (T) = - 0.4084 + 1.0468Fs. The – 0.4084 is the constant value for determining the splitting tensile strength of the RCPBs. The 1.0468 means if flexural strength (Fs) is increased by one unit splitting tensile strength will on average increase by 1.0468. A Pearson correlation was conducted to determine whether the correlation is statistically significant. It was found that r = 0.998 and $P < 0.001$ (Table 4.19). Positive value of 'r' indicates that as flexural strength increases, splitting tensile strength increases. $P < 0.001$ shows that the correlation is statistically significant.

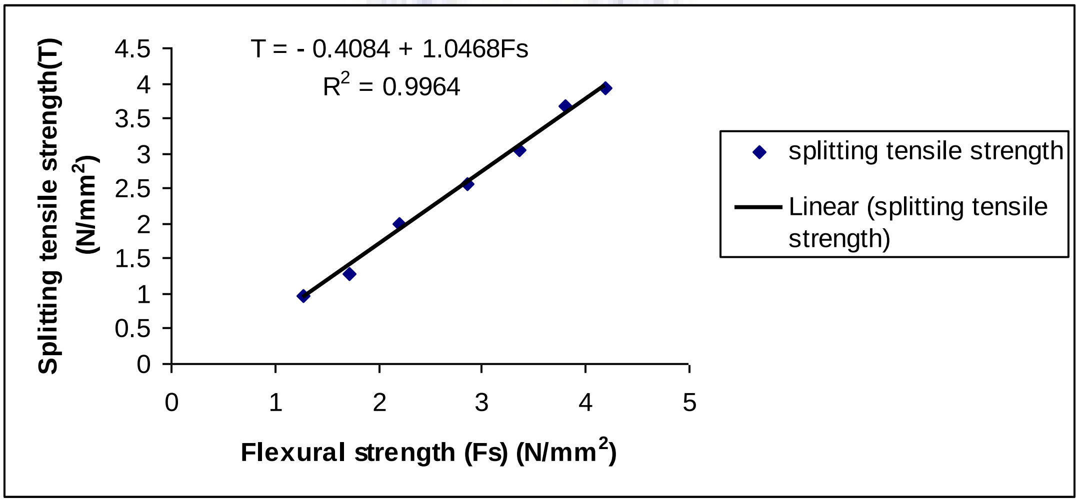


Figure 4.10: Relationship between flexural strength and splitting tensile strength

Table 4.19: Pearson correlation showing the statistical significance of the correlation between flexural strength and splitting tensile strength

		Flexural strength	Splitting tensile strength
Flexural strength	Pearson Correlation	1	.998**
	Sig. (1-tailed)		.000
	N	7	7
Splitting tensile strength	Pearson Correlation	.998**	1
	Sig. (1-tailed)	.000	
	N	7	7

**. Correlation is significant at the 0.01 level (1-tailed).

4.8 Development of Models for Predicting the Density and Compressive Strength

The models were developed based on the experimental results presented in Table 4.20. The multiple regression analysis was selected for developing the predictive models with the aid of Statistical Package for the Social Sciences (SPSS) version 16. Multiple regression analysis is by far the most widely used multivariate technique to analyse the relationship between several independent variables and a single dependent variable (Hair, Anderson & Tatham, 1998). Thus multiple regressions offer the opportunity to establish the evidence that one or more explanatory variables (independent variables, X_1, X_2, X_3…..X_k) cause another dependent variable Y to change (Blaikie, 2003). In so doing, the analysis establishes the relative magnitude of the contribution of each predictor variable. Furthermore, it offers the opportunity to examine what proportion of the variance in the outcome variable is explained by each predictor variable and / or their combined effect (Brace, Kemp & Snelgal, 2003). Using the classical linear regression model, the relation between the predicted outcome Yp and the predictor variables, X_1, X_2,…..X_k is defined as: $Yp = \alpha + \beta_1X_1 + \beta_2X_2 + \ldots\ldots\ldots\ldots \beta_kX_k + \varepsilon$; where α = a constant on the Y-axis, B_1 to B_k are the coefficients of interest, X_1 to X_k are the independent variables and ε is the error term. In this case the independent variables were represented by W/C ratio and GVT while the dependent variable (Yp) was density or compressive strength of RCPBs.

Table 4.20: The experimental testing results of density and compressive strength

Water cement ratio	Rubber content (%)	Density (kg/m^3)	Compressive strength (N/mm^2)
0.20	0	2125.31	17.30
	10	2116.60	14.39
	20	2047.61	11.18
	30	1978.63	9.11
	40	1909.65	6.10
	50	1840.67	3.63
	60	1771.69	2.48
0.25	0	2180.90	22.40
	10	2139.29	18.62
	20	2070.32	14.47
	30	2001.33	11.79
	40	1932.35	7.89
	50	1863.37	4.69
	60	1794.39	3.20
0.30	0	2250.10	26.10
	10	2162.00	21.69
	20	2093.02	16.85
	30	2024.04	13.74
	40	1955.05	9.16
	50	1886.07	5.44
	60	1817.10	3.70
0.35	0	2229.35	30.20
	10	2184.70	25.10
	20	2115.72	19.50
	30	2046.74	15.90
	40	1977.76	10.60
	50	1908.78	6.30
	60	1839.80	4.30

4.8.1 Model for predicting the density of the produced RCPBs

Enter selection technique was used for the analysis. The enter method is the default method for multiple regression. It is also known as direct regression or simultaneous regression. In this technique, all the predictor variables are tested at once. Table 4.21 presents the model summary of the results for the regression analysis. The R square (R^2) which is the coefficient of determination shows that there is strong correlation between the dependent variable (density) and the independent variables (GVT and W/C ratio). However, R^2 tends to somehow over-estimate the success of the model when applied to the real world, so an adjusted R^2 value is calculated which takes into account the number of variables in the models and the number of observations (i.e. participants) the model is based on (Brace et al.,2003). Thus, the adjusted R^2 is useful because it gives an indication of how much of the variance in the density is accounted for in the population from which the samples were chosen. Subsequently, using the adjusted R^2 and the analysis of variance (ANOVA) (Table 4.22), the following conventional statistical report was extracted (Adjusted $R^2 = 99.1\%$, $F_{2, 25} = 1550$, $P < 0.001$). The P-value reported in Table 4.22 assesses the overall significance of the model. As $P < 0.001$, it demonstrates that the model is significant. The emerged model indicates that 99.1% of the variation in the density of RCPBs can be explained by the two variables (GVT and W/C ratio). The unstandardized coefficients B column (Table 4.23) gives the coefficients of the independent variables in the regression equation including all the predictor variables. Table 4.23 also shows that the effect of W/C ratio and GVT on the prediction of density is statistically significant ($P < 0.001$). Subsequently, the following model for predicting the density of the produced RCPBs is derived:

Density of RCPBs = 2071.861+ 498.143 W/C ratio – 6.649 GVT content.

(Adjusted R^2) = 99.1%

The 2071.861 is a constant value for predicting the density of RCPBs. The 498.143 means if W/C ratio is increased by one unit density of RCPBs will on average increase by 498.143. The – 6.649 means if GVT is increased by one unit density of RCPBs will on average decrease by 6.649. The adjusted R^2 = 99.1% indicates that 99.1% of the variation in density can be explained by W/C ratio and GVT content.

Table 4.21: Model summary of the regression analysis

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.996[a]	.992	.991	12.91213

a. Predictors: (Constant), GVT content, water cement ratio

Table 4.22: Analysis of Variance showing the significance of the regression model

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	516911.706	2	258455.853	1.550E3	.000[a]
	Residual	4168.079	25	166.723		
	Total	521079.785	27			

a. Predictors: (Constant), GVT content, water cement ratio

b. Dependent Variable: Density

Table 4.23: Coefficients table showing the coefficients of the independent variables in the regression equation

Model		Unstandardized Coefficients		Standardized Coefficients		
		B	Std. Error	Beta	t	Sig.
1	(Constant)	2071.861	12.785		162.058	.000
	water cement ratio	498.143	43.651	.204	11.412	.000
	GVT content	-6.649	.122	-.975	-54.499	.000

a. Dependent Variable: Density

4.8.1.1 Test of goodness of fit

The adjusted R^2 of 99.1% is very high and this suggests that the model is relatively good. Analysis of variance (ANOVA) (Table 4.22) also indicates that the regression equation is statistically significant ($P < 0.001$). These parameters are indications of the goodness of fit of the model.

4.8.2 Model for predicting the compressive strength of the produced RCPBs

Enter selection technique was used for the analysis. Table 4.24 presents a summary of the results for the regression analysis. The $R^2 = 0.957$ indicates that there is strong correlation between the dependent variable (compressive strength) and the independent variables (GVT and W/C ratio). The table also shows that the adjusted $R^2 = 0.953$. Using the adjusted R^2 and the ANOVA (Table 4.25), the following conventional statistical report was extracted (adjusted $R^2 = 95.3\%$, $F_{2, 25} = 275.486$, $P < 0.001$). The P-value reported in Table 4.25 assesses the overall significance of the model. As $P < 0.001$, it demonstrates that the model is significant. The emerged model shows that 95.3% of the variation in the compressive strength can be explained by the two independent variables

(GVT and W/C ratio). The unstandardized coefficients B column (Table 4.26), gives the coefficients of the independent variables in the regression equation including all the predictor variables. Table 4.26 also exhibits that the effect of W/C ratio and GVT on the prediction of compressive strength is statistically significant ($P < 0.001$). Subsequently, the following model for predicting the compressive strength is derived:

Compressive strength of RCPBs = 10.964 + 44.786 W/C ratio − 0.352 GVT content. (Adjusted R^2) = 95.3%

The 10.964 is a constant value for predicting the compressive strength of the RCPBs. The 44.786 means if W/C ratio is increased by one unit compressive strength of RCPBs will on average increase by 44.786. The – 0.352 means if GVT is increased by one unit compressive strength of RCPBs will on average decrease by 0.352. The adjusted R^2 = 95.3% indicates that 95.3% of the variation in compressive can be explained by W/C ratio and GVT content.

Table 4.24: Model summary of the regression analysis

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.978[a]	.957	.953	1.68611

a. Predictors: (Constant), rubber content, water cement ratio

b. Dependent Variable: compressive strength

Table 4.25: Analysis of variance showing the significance of the regression model

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	1566.399	2	783.199	275.486	.000[a]
	Residual	71.074	25	2.843		
	Total	1637.473	27			

a. Predictors: (Constant), rubber content, water cement ratio

b. Dependent Variable: compressive strength

Table 4.26: Coefficients table showing the coefficients of the independent variables in the regression equation

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	10.964	1.669		6.567	.000
	water cement ratio	44.786	5.700	.327	7.857	.000
	GVT content	-.352	.016	-.922	-22.119	.000

a. Dependent Variable: compressive strength

4.8.2.1 Test of goodness of fit

The adjusted R^2 of 95.3% is very high and this suggests that the model is relatively good. Analysis of variance (ANOVA) (Table 4.25) also indicates that the regression equation is statistically significant ($P < 0.001$). These parameters are indications of the goodness of fit of the model.

CHAPTER FIVE

DISCUSSION OF RESULTS

5.0 Introduction

This chapter discusses the results of the study presented in line with the objectives of the study. It commences by discussing the results of the physical and mechanical properties of RCPBs. Relationship between properties of RCPBs are also discussed. Finally, the chapter discusses the models developed to predict the density and compressive strength of the produced RCPBs.

5.1 Physical Properties of RCPBs

5.1.1 Density

5.1.1.1 Effect of W/C ratio and GVT

It was observed that the density of RCPB increased as the W/C ratio increased (Table 4.9). The density increased by about 3.5% when W/C ratio of 0.35 was used irrespective of the rubber content used. The differences in density may be attributed to the different quantities of water used for the preparation of the RCPBs. W/C ratio of 0.20 was found to be very small. Mixes produced from W/C ratio of 0.20 were very dry and difficult to compact and consequently it affected the denseness of the aggregate within those batches. However, the dryness of the mixes reduced as the W/C ratio moved from 0.20 to 0.35 which provided a good compaction and resulted in less empty spaces between the aggregate particles and the cement paste. Practically, it means that the masses of the RCPBs increased as the W/C ratio increased from 0.20 to 0.35. The finding is supported by Ling (2011) who reported that the density of RCPB increased about 2.9% as the W/C ratio moved from 0.45 to 0.55 regardless of the rubber content used.

It was also noticed that the density of RCPB decreased as the rubber content increased (Table 4.9). The density reduction pattern was similar for the four different W/C ratios. The density was reduced by about 18% when 60% of the total sand was replaced by rubber regardless of the W/C ratio used. This may be due to the low specific gravity of GVT (1.12) as compared to sand (2.60). The difference in the specific gravities shows that sand is heavier than GVT. Partially replacing volume of the sand by GVT would certainly reduce the masses of the RCPBs. This indicates that once the percentage (%) of the volume replacement of the sand by GVT increases the reduction of the masses of the RCPBs also increases. Siddique and Naik (2004) reported that the non-polar nature of rubber particles may tend to entrap air if their rough surface increase, which in turn increases the air content and reduces the density of the concrete mixtures. The result is supported by Liet et al. (1998) who mentioned that the density of rubberized concrete was lowered by approximately 10% when 35% volume of the sand was replaced by crumb rubber. Similarly, Ling (2011) reported that the dry density of RCPB reduced about 8% when 50% of the sand was substituted with crumb rubber. Mavroulidou and Figuiredo (2010) also found that the density of rubberized concrete decreased about 76% when 40% of the fine mineral aggregate was replaced by fine rubber aggregate.

5.1.2 Water absorption

It was noticed that water absorption of RCPBs increased as the rubber content increased (Table 4.11). The water absorption moved from 1.44% to 1.76%, indicating an increase of about 22% when 60% of the total sand was replaced by GVT. The rise may be due to the increase of voids in RCPBs as a result of the weak bond between the rubber particles and the cement paste. The result is in agreement with the findings of Ling et al. (2010) who mentioned that the water absorption of RCPB increased by about 25% when 50% of the fine aggregate was replaced by crumb rubber.

5.2. Mechanical Properties of RCPBs

5.2.1 Compressive strength

5.2.1.1 Effect of W/C ratio and GVT

It was noticed that compressive strength of RCPBs increased as the W/C ratio increased (Table 4.12). The compressive strength was raised by about 42% when W/C ratio of 0.35 was used regardless of the GVT content used. A possible reason for this increase in strength may be due to the different quantities of water used for the preparation of the RCPBs. Concrete required certain amount of water for it to achieve its maximum strength during the hydration reaction of the cement paste. W/C ratio of 0.20 was found to be very small and as a result there was insufficient water in the spaces between the cement grains to convert each grain of the cement into gel. The inner cores of the cement particles were therefore not hydrated well and consequently it affected the strength of the RCPBs. However, the increase in W/C ratio from 0.20 to 0.35 helped the cement paste to achieve the water needed for the hydration reaction, thereby increasing the strength of the concrete. W/C ratio of 0.35 was found to be the optimum W/C ratio within the range (0.20 – 0.35) and as a results the maximum strength was achieved when it was used. The result is consistent with the findings of Ling (2011) who reported that the compressive strength of RCPBs increased about 30% as the W/C ratio moved from 0.45 to 0.55 irrespective of the rubber content used. However, Azmi et al. (2008) reported that the compressive strength of rubberized concrete decreased as the W/C ratio increased. The compressive strength decreased from 39.68 N/mm^2 to 18.2 N/mm^2 when the W/C ratio moved from 0.41 to 0.68.

It was also observed that the compressive strength decreased as the GVT content increased (Table 4.12). The decrease pattern of the compressive strength was similar for the four different W/C ratios. The compressive strength was decreased by about 86% when 60% of the total sand was substituted with rubber regardless of the W/C ratio used. The reason for the reduction could be attributed to the smooth surfaces of rubber particles which might have reduced the adhesion between the boundaries of the rubber particles and the cement paste. The finding is supported by Azmi et al. (2008) who observed that there was a decrease of about 35% in compressive strength of rubberized concrete when 30% of the fine aggregate was replaced by crumb rubber. Similarly, Eldin and Senouci (1993) reported that there was a reduction of about 65% in compressive strength when fine aggregate was fully replaced by crumb rubber. Ling (2008) also mentioned that there was a slump of about 52% in compressive strength of RCPBs when 30% of the total sand was substituted with rubber. A reduction in compressive strength of about 92.6% was further reported by Mavoulidou and Figuiredo (2010) when fine mineral aggregate was partially replaced by 40% fine rubber aggregate.

5.2.1.2 Effect of curing age

It was noticed that compressive strength increased as the curing age increased regardless of the GVT content used (Figure 4.4). The compressive strength was increased about 26% when the curing age moved from 7 days to 28 days irrespective of the GVT content used. The increase in strength may be due to the hydration reaction of the cement paste which increases the strength of concrete as curing age increases. The finding is in agreement with Ling (2008) who mentioned that the compressive strength of RCPBs increased about 23% when the curing age moved from 7 days to 28 days. Similarly, Azmi et al. (2008) reported that compressive strength of rubberized concrete increased as the curing age increased. With 15% replacement of sand with crumb rubber, the compressive strength increased from 17.7 N/mm^2 to 20.13 N/mm^2 when the curing age moved from 7 days to 28 days for W/C ratio of 0.41.

5.2.2. Flexural strength

5.2.2.1 Effect of GVT

It was observed that as the rubber content increased the flexural strength decreased (Table 4.14). The flexural strength decreased from 4.18N/mm^2 to 1.28 N/mm^2, indicating a reduction of about 69% when 60% volume of the sand was replaced with GVT. The reduction in strength may be influenced by the weak bond between the rubber particles and the cement paste in the mix. The result is consistent with the findings of Azmi et al. (2008) who mentioned that there was a reduction of about 20% in flexural strength when 30% of the fine aggregate was replaced by crumb rubber for water cement ratio of 0.41. Mavroulidou and Figueiredo (2010) also reported that there was a slump of about 22% in modulus of rupture when 40% of the fine aggregate was substituted with rubber. Similarly, Khatib and Bayomy (1999) mentioned a reduction of 90% in flexural strength when the fine aggregate was fully replaced by crumb rubber.

5.2.2.2 Effect of curing age

It was found that flexural strength increased as the curing age increased irrespective of the GVT content used (Figure 4.5). The flexural strength was increased by about 25% when the curing age moved from 7 days to 28 days regardless of the GVT content used. The increase in strength may be due to the hydration reaction of the cement paste which increases the strength of concrete as curing age increases. The finding is supported by Ling (2008) who mentioned that the flexural strength of RCPB increased as the curing age increased. The flexural strength increased about 25% when the curing age moved from 7 days to 28 days for 20% replacement of crumb rubber. Azmi et al. (2008) also reported that the flexural strength of crumb rubber concrete increased as the curing age increased. With 10% replacement of sand with crumb rubber, the flexural strength of the rubberized concrete increased from 7.1 N/mm^2 to 9.4 N/mm^2 when the curing age moved from 7 days to 28 days for W/C ratio of 0.41

5.2.3 Splitting tensile strength

5.2.3.1 Effect of GVT

It was noticed that as the rubber content increased the splitting tensile strength reduced (Table 4.15). The splitting tensile strength decreased from 3.92N/mm^2 to 0.97 N/mm^2, indicating a reduction of about 75% when 60% volume of the sand was substituted with GVT. The reduction may be attributed to the weak adhesion between the rubber particles and the cement paste in the mix. The finding is supported by Azmi et al. (2010) who reported that there was a reduction of about 15% in splitting tensile value when 30% of the fine aggregate was replaced by rubber. Similarly, Eldin and Senouci (1993) mentioned that there was a slump of about 50% in splitting tensile strength when the fine aggregate was fully replaced by crumb rubber. Mavroulidou and Figueiredo (2010) also reported a decrease of about 30% in splitting tensile strength when 40% of the fine aggregate was substituted with crumb rubber.

5.2.3.2 Effect of curing age

It was seen that splitting tensile strength increased as the curing age increased regardless of the GVT content used (Figure 4.6). The splitting tensile strength was increased by about 26% when the curing age moved from 7 days to 28 days regardless of the GVT content used. The increase in strength may be attributed to the hydration reaction of the cement paste which increases the strength of concrete as curing age increases. The finding is supported by Ling (2008) who mentioned that the splitting tensile strength of RCPB increased about 24% when the curing age moved from 7 days to 28 days. An increase of about 21% in splitting tensile strength of rubberized concrete was reported by Mavroulidou and Figueiredo (2010) when the curing age moved from 7 days to 28 days.

5.3 Relationship between Properties of Rubberized Concrete Pavement Blocks

5.3.1 Density and compressive strength

It was noticed that there was a linear correlation between density and compressive strength (Figure 4.7). The correlation between density and compressive strength was found to be statistically significant [(r = 0.995 and P < 0.001(Table 4.16)]. The relationship between the density and the compressive strength may be due to the correlation between the compressive force and the mass of the blocks. The result is supported by Ling (2012) who reported that there was a linear correlation between density and compressive strength of RCPBs.

5.3.2 Compressive strength and flexural strength

It was observed that there was a linear correlation between compressive strength and flexural strength (Figure 4.8). The correlation between compressive strength and flexural strength was found to be statistically significant [(r = 0.992 and P < 0.001(Table 4.17)]. The relationship between the flexural strength and the compressive strength may be attributed to the correlation between the compressive force and the flexural force required to break the RCPBs. The result is in consistent with the findings of Ling (2010) who reported that there was a linear correlation between compressive strength and flexural strength of RCPBs.

5.3.3 Compressive strength and splitting tensile strength

It was noticed that there was a linear correlation between compressive strength and splitting tensile strength (Figure 4.9). The correlation between compressive strength and splitting tensile strength was found to be statistically significant [(r = 0.991 and P < 0.001(Table 4.18)]. The relationship between the splitting tensile strength and the compressive strength may be influenced by the correlation between the compressive force and the tensile force required to break the RCPBs. The result is in agreement with the findings of Ling (2008) who reported that there was a linear correlation between compressive strength and splitting tensile strength of RCPBs.

5.3.4 Flexural strength and splitting tensile strength

It was observed that there was a linear correlation between flexural strength and splitting tensile strength (Figure 4.10). The correlation between flexural strength and splitting tensile strength was found to be statistically significant [(r = 0.998 and P < 0.001(Table 4.19)]. The relationship between the splitting tensile strength and the flexural strength may be due to the correlation between the flexural force and the tensile force required to break the RCPBs. The result is in agreement with the findings of Ling (2008) who reported that there was a positive correlation between flexural strength and splitting tensile strength of RCPBs.

5.4 Development of Models for Predicting the Density and Compressive Strength

5.4.1 Model for predicting the density of the produced RCPBs

Model for predicting the density of the produced RCPBs was determined as: Density of RCPBs = 2071.861 + 498.143 W/C ratio – 6.649 GVT content (Adjusted R^2 = 99.1%). The 2071.861 is a constant value for predicting the density of RCPBs. The 498.143 means if W/C ratio is increased by one unit density of RCPBs will on average increase by 498.143. The – 6.649 means if GVT is increased by one unit density of RCPBs will on average decrease by 6.649. The adjusted R^2 = 99.1% indicates that 99.1% of the variation in density can be explained by W/C ratio and GVT content. The standardised regression co-efficient (i.e. beta), the t-values and the respective P – values reported in Table 4.23 indicate the significant contribution of W/C ratio and GVT in predicting the density of the RCPBs. The beta values are measures of how strongly each variable influence the prediction of the density. For a variable to be deemed as making a significant contribution, the beta value should differ significantly from zero (Field, 2005). The beta values indicate that W/C ratio has positive influence on the prediction of density while GVT content has a negative influence. The t – values provide a test of the hypothesis that the beta values differ significantly from zero (i.e. P – value should be less than 0.05). This also enables us to see which predicators are significant. It can be observed that both W/C ratio and GVT are statistically significant ($P < 0.001$) when predicting the density of RCPBs. The model is supported by Ling (2011) who reported that W/C ratio and rubber content have significant effect on predicting the density of RCPBs. However, the current equation is different from that of Ling's. This is because the experimental results used to develop the equation were obtained from different range of W/C ratios and different fix aggregate/cement ratio.

5.4.2 Model for predicting the compressive strength of the produced RCPBs

Model for predicting the compressive strength of the produced RCPBs was determined as:

Compressive strength of RCPBs = 10.964 + 44.786 W/C ratio − 0.352 GVT content. (Adjusted R^2 = 95.3%). The 10.964 is a constant value for predicting the compressive strength of RCPBs. The 44.786 means if W/C ratio is increased by one unit compressive strength of RCPBs will on average increase by 44.786. The – 0.352 means if GVT is increased by one unit compressive strength of RCPBs will on average decrease by 0.352. The adjusted R^2 = 95.3% indicates that 95.3% of the variation in compressive can be explained by W/C ratio and GVT content. The beta values in Table 4.26 show the contribution of W/C ratio and GVT in predicting the compressive of the RCPBs. The beta values indicate that W/C ratio has positive influence on the prediction of compressive strength while GVT content has a negative influence. The P – values suggest that the beta values differ significantly from zero, confirming the relatively stronger contribution of W/C ratio and GVT to the prediction of the RCPBs. The model is supported by Ling (2011) who reported that W/C ratio and rubber content have significant effect on predicting the compressive strength of RCPBs. However, the current equation is different from that of Ling's. This is because the experimental results used to develop the equation were obtained from different range of W/C ratios and different fix aggregate/cement ratio.

CHAPTER SIX

SUMMARY OF FINDINGS, CONCLUSIONS AND RECOMMENDATIONS

6.0 Introduction

This chapter summarizes the major findings of the study and draws conclusions based on the results. Recommendations are then made to help utilize the accumulation of waste vehicular tyres in the production of concrete pavement blocks in Ghana.

6.1 Summary of Findings

The use of GVT as partial replacement for sand in the production of concrete pavement blocks was found to have effect on both physical and mechanical properties of rubberized concrete pavement blocks. Decrease in density, compressive strength, flexural strength, and splitting tensile strength was observed when part of the sand was substituted with GVT. The rate of reduction in the strengths of RCPBs increased as the percentage of the GVT increased. However, the water absorption of RCPBs increased as the GVT content increased. Water cement ratio was found to have effect on the density and compressive strength of the RCPBs. The effect of water cement ratio on the compressive strength was higher than that of density. Curing age was also found to have effect on the strengths of the RCPBs. The compressive strength, flexural strength, and splitting tensile strength increased as the curing age increased. It was also realized that there was a positive correlation between density and compressive strength, compressive strength and flexural strength, compressive strength and splitting tensile strength, and flexural strength and splitting tensile strength. In all cases, the correlation was found to be statistically significant. Water cement ratio and GVT were found to have significant effect in predicting the density and the compressive strength of RCPBs.

6.2 Conclusions

The use of GVT as partial replacement for sand in the production of RCPBs reduces the strengths of the blocks. Although, the strengths of RCPBs decreases as the GVT content increases, a compressive strength of 25.10 N/mm^2 could be achieved if 10% GVT and W/C ratio of 0.35 is used. Such rubberized concrete pavement blocks are capable to be used for pedestrians walk ways, which required a minimum compressive strength of 20N/mm^2. The developed models are possible to predict the density and compressive strength of the RCPBs, if the W/C ratio used are within the tested ranged (0.20 – 0.35). The models will help to facilitate the production of the developed RCPBs. This study has contributed to the exiting knowledge of rubberized concrete pavement blocks so far as water cement ratio in the range of 0.20 to 0.35 is concerned.

6.3 Recommendations

i. It is recommended that a body should be formed by the government through Ministry of Science and Environment to take care of the waste vehicular tyres in the country. The body should be tasked to process the tyre and stock them in order to make the processed tyres available to the companies that produce pavement blocks. Incentives should be given to people who will provide the waste tyres to the organization.

ii. It is also recommended that policies that will make contractors to utilize the processed waste tyres in pedestrians walk ways pavement blocks should be formulated, especially for government projects.

iii. It is recommended that further studies should be conducted into this study in order to extend the findings of the work. The effect of GVT on properties like skip resistance, abrasion resistance, and toughness which were not covered in this study should be considered. The effect of the use of de-airy agent in RCPBs should be carried out. Finally, effect of long term curing age on RCPBs should be considered in future studies.

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APPENDICES

Appendix – A: Test results for physical properties of materials

A1: Physical properties of sand

Description	Results
1. Fineness modulus	
∑ cumulative % retained	250.42
Fineness modulus = ∑ cumulative % retained / 100	2.50
2. Compacted bulk density	
Mass of sand (M)	3.3 kg
Volume of sand (V)	1.9446×10^{-3} m^3
Compacted bulk density = M / V	1697 kg/m^3
3. Bulk specific gravity and bulk specific gravity SSD	
A = mass of oven-dry sample in air	479g
S = mass of saturated surface-dry sample in air	500.0g
B = mass of flask filled with water	1271.0g
C = mass of flask with specimen and water to the Calibration mark	1586.8
Bulk specific gravity = A/(S+B-C)	2.60
Bulk specific gravity SSD = S/(S+B-C)	2.71
4. Particle density	
Specific gravity of sand	2.60
Density of water	1g/cm^3
Particle density = specific gravity x density of water	2.60g/cm^3
5. Moisture content	
W = mass of the original sample	500g
W_{OD} = mass of dried sample	490.48g
Moisture content = [(W – W_{OD}) / W_{OD}] x 100	1.94%
6. Silt content	
H = height of soil in glass	144mm
Hs = height of silt in the soil	4.10mm
Silt content = (H / Hs) x 100	2.85%

A2: Physical properties of quarry dust

Description	Results
1. Fineness modulus	
$\sum$ cumulative % retained	311.09
Fineness modulus = $\sum$ cumulative % retained / 100	3.11
2. Compacted bulk density	
Mass of quarry dust (M)	3.3kg
Volume of quarry dust (V)	$1.9446 \times 10^{-3} m^3$
Compacted bulk density = M / V	1697 kg/m^3
3. Bulk specific gravity and bulk specific gravity SSD	
A = mass of oven-dry sample in air	478g
S = mass of saturated surface-dry sample in air	500g
B = mass of flask filled with water	1271g
C = mass of flask with specimen and water to the calibration mark	1587g
Bulk specific gravity = A/(S+B-C)	2.60
Bulk specific gravity SSD = S/(S+B-C)	2.72
4. Particle density	
Specific gravity of quarry dust	2.60
Density of water	1g/cm^3
Particle density = specific gravity x density of water	2.60g/cm^3
5. Moisture content	
W = mass of the original sample	500g
W_{OD} = mass of dried sample	491.01g
Moisture content = [(W – W_{OD}) / W_{OD}] x 100	1.83%

A3: Physical properties of coarse aggregate

Description	Results
1. Fineness modulus	
$\sum$ cumulative % retained	197.2
Fineness modulus = $\sum$ cumulative % retained/100	1.97
2. Compacted bulk density	
Mass of coarse aggregate (M)	3.348kg
Volume of coarse aggregate (V)	$1.9446 \times 10^{-3} m^3$
Compacted bulk density = M / V	1722kg/m^3

Continuation of A3

Description	Results
3. Bulk specific gravity and bulk specific gravity SSD	
A = mass of oven-dry sample in air	483.70g
B = mass of saturated surface-dry sample in air	500.0g
C = apparent mass of saturated sample immersed is water	324.1g
Bulk specific gravity = A / (B – C)	2.75
Bulk specific gravity SSD = B / (B – C)	2.84
4. Particle density	
Specific gravity of coarse aggregate	2.75
Density of water	$1 g/cm^3$
Particle density = specific gravity x density of water	$2.75 g/cm^3$
5. Moisture content	
W = mass of the original sample	500g
W_{OD} = mass of dried sample	493.2g
Moisture content = $[(W – W_{OD}) / W_{OD}] \times 100$	1.38%

A4: Physical properties of ground vehicular tyre (GVT)

Description	results
1. Fineness modulus	
∑ cumulative % retained	130.88
Fineness modulus = ∑ cumulative % retained / 100	1.31
2. Compacted bulk density	
Mass of GVT (M)	0.9kg
Volume of GVT (V)	$1.9446 \times 10^{-3} m^3$
Compacted bulk density = M / V	$463 kg/m^3$
3. Specific gravity	
Wa = mass of original sample	50g
Wb = mass of flask filled with rubber and alcohol	1220g
Wc = mass of flask filled with alcohol	1205g
D = density of alcohol	$0.789 g/cm^3$
Specific gravity of GVT = [(0.9971 x Wa) x D] / [Wa – (Wb - Wc)]	1.12
4. Particle density of GVT	
Specific gravity of GVT (S)	1.12
Density of alcohol (D)	$0.789 g/cm^3$
Particle density of GVT = S x D	$0.9 g/cm^3$

Appendix – B: Test results for physical properties of RCPBs

B1: 28 day density test results

Batch	Dimensions of specimen			Volume(V) (m^3)	Weight(M) (kg)	Density(M/V) (kg/m^3)
	Length(m)	Width(m)	Height(m)			
A0.2	0.2	0.1	0.06	1.2×10^{-3}	2.552	2126.53
	0.2	0.1	0.06	1.2×10^{-3}	2.542	2118.30
	0.2	0.1	0.06	1.2×10^{-3}	2.565	2137.50
	0.2	0.1	0.06	1.2×10^{-3}	2.535	2112.50
	0.2	0.1	0.06	1.2×10^{-3}	2.558	2131.67
	Mean			1.2×10^{-3}	2.550	2125.30
A0.25	0.2	0.1	0.06	1.2×10^{-3}	2.601	2167.50
	0.2	0.1	0.06	1.2×10^{-3}	2.605	2170.83
	0.2	0.1	0.06	1.2×10^{-3}	2.629	2190.83
	0.2	0.1	0.06	1.2×10^{-3}	2.633	2194.17
	0.2	0.1	0.06	1.2×10^{-3}	2.618	2181.17
	Mean			1.2×10^{-3}	2.617	2180.90
A0.30	0.2	0.1	0.06	1.2×10^{-3}	2.711	2259.17
	0.2	0.1	0.06	1.2×10^{-3}	2.681	2234.17
	0.2	0.1	0.06	1.2×10^{-3}	2.689	2240.83
	0.2	0.1	0.06	1.2×10^{-3}	2.700	2250.50
	0.2	0.1	0.06	1.2×10^{-3}	2.719	2265.83
	Mean			1.2×10^{-3}	2.700	2250.10
A0.35	0.2	0.1	0.06	1.2×10^{-3}	2.724	2270.00
	0.2	0.1	0.06	1.2×10^{-3}	2.695	2245.83
	0.2	0.1	0.06	1.2×10^{-3}	2.712	2260.09
	0.2	0.1	0.06	1.2×10^{-3}	2.727	2272.50
	0.2	0.1	0.06	1.2×10^{-3}	2.698	2248.33
	Mean			1.2×10^{-3}	2.711	2259.35
B10/0.20	0.2	0.1	0.06	1.2×10^{-3}	2.549	2124.17
	0.2	0.1	0.06	1.2×10^{-3}	2.540	2116.32
	0.2	0.1	0.06	1.2×10^{-3}	2.522	2101.60
	0.2	0.1	0.06	1.2×10^{-3}	2.531	2109.17
	0.2	0.1	0.06	1.2×10^{-3}	2.558	2131.67
	Mean			1.2×10^{-3}	2.540	2116.60

Continuation of B1

Batch	Dimensions of specimen			Volume(V) (m^3)	Weight(M) (kg)	Density(M/V) (kg/m^3)
	Length(m)	Width(m)	Height(m)			
B10/0.25	0.2	0.1	0.06	1.2 x 10^{-3}	2.568	2139.79
	0.2	0.1	0.06	1.2 x 10^{-3}	2.584	2153.33
	0.2	0.1	0.06	1.2 x 10^{-3}	2.577	2147.50
	0.2	0.1	0.06	1.2 x 10^{-3}	2.550	2125.00
	0.2	0.1	0.06	1.2 x 10^{-3}	2.557	2130.83
	Mean			1.2 x 10^{-3}	2.567	2139.29
B10/0.30	0.2	0.1	0.06	1.2 x 10^{-3}	2.608	2173.33
	0.2	0.1	0.06	1.2 x 10^{-3}	2.580	2150.00
	0.2	0.1	0.06	1.2 x 10^{-3}	2.582	2151.67
	0.2	0.1	0.06	1.2 x 10^{-3}	2.610	2175.00
	0.2	0.1	0.06	1.2 x 10^{-3}	2.592	2160.00
	Mean			1.2 x 10^{-3}	2.595	2162.00
B10/0.35	0.2	0.1	0.06	1.2 x 10^{-3}	2.630	2191.67
	0.2	0.1	0.06	1.2 x 10^{-3}	2.624	2186.82
	0.2	0.1	0.06	1.2 x 10^{-3}	2.606	2171.67
	0.2	0.1	0.06	1.2 x 10^{-3}	2.612	2176.67
	0.2	0.1	0.06	1.2 x 10^{-3}	2.636	2196.67
	Mean			1.2 x 10^{-3}	2.621	2184.70
B20/0.20	0.2	0.1	0.06	1.2 x 10^{-3}	2.458	2048.05
	0.2	0.1	0.06	1.2 x 10^{-3}	2.440	2033.33
	0.2	0.1	0.06	1.2 x 10^{-3}	2.466	2055.00
	0.2	0.1	0.06	1.2 x 10^{-3}	2.474	2061.67
	0.2	0.1	0.06	1.2 x 10^{-3}	2.448	2040.00
	Mean			1.2 x 10^{-3}	2.457	2047.61
B20/0.25	0.2	0.1	0.06	1.2 x 10^{-3}	2.496	2080.00
	0.2	0.1	0.06	1.2 x 10^{-3}	2.485	2071.60
	0.2	0.1	0.06	1.2 x 10^{-3}	2.501	2084.17
	0.2	0.1	0.06	1.2 x 10^{-3}	2.467	2055.83
	0.2	0.1	0.06	1.2 x 10^{-3}	2.472	2060.00
	Mean			1.2 x 10^{-3}	2.484	2070.32
B20/0.30	0.2	0.1	0.06	1.2 x 10^{-3}	2.523	2102.50
	0.2	0.1	0.06	1.2 x 10^{-3}	2.530	2108.33
	0.2	0.1	0.06	1.2 x 10^{-3}	2.494	2078.33
	0.2	0.1	0.06	1.2 x 10^{-3}	2.510	2091.77
	0.2	0.1	0.06	1.2 x 10^{-3}	2.501	2084.17
	Mean			1.2 x 10^{-3}	2.512	2093.02
B20/0.35	0.2	0.1	0.06	1.2 x 10^{-3}	2.552	2126.67
	0.2	0.1	0.06	1.2 x 10^{-3}	2.538	2115.26
	0.2	0.1	0.06	1.2 x 10^{-3}	2.523	2102.50

Continuation of B1

Batch	Dimensions of specimen			Volume(V) (m^3)	Weight(M) (kg)	Density(M/V) (kg/m^3)
	Length(m)	Width(m)	Height(m)			
B20/0.35	0.2	0.1	0.06	1.2×10^{-3}	2.555	2129.17
	0.2	0.1	0.06	1.2×10^{-3}	2.526	2105.00
	Mean			1.2×10^{-3}	2.539	2115.72
B30/0.20	0.2	0.1	0.06	1.2×10^{-3}	2.393	1994.17
	0.2	0.1	0.06	1.2×10^{-3}	2.359	1965.83
	0.2	0.1	0.06	1.2×10^{-3}	2.376	1979.82
	0.2	0.1	0.06	1.2×10^{-3}	2.389	1990.83
	0.2	0.1	0.06	1.2×10^{-3}	2.355	1962.50
	Mean			1.2×10^{-3}	2.372	1978.63
B30/0.25	0.2	0.1	0.06	1.2×10^{-3}	2.416	2013.33
	0.2	0.1	0.06	1.2×10^{-3}	2.393	1994.17
	0.2	0.1	0.06	1.2×10^{-3}	2.411	2009.17
	0.2	0.1	0.06	1.2×10^{-3}	2.400	1999.98
	0.2	0.1	0.06	1.2×10^{-3}	2.388	1990.00
	Mean			1.2×10^{-3}	2.402	2001.33
B30/0.30	0.2	0.1	0.06	1.2×10^{-3}	2.447	2039.17
	0.2	0.1	0.06	1.2×10^{-3}	2.428	2023.53
	0.2	0.1	0.06	1.2×10^{-3}	2.416	2013.33
	0.2	0.1	0.06	1.2×10^{-3}	2.442	2035.00
	0.2	0.1	0.06	1.2×10^{-3}	2.411	2009.17
	Mean			1.2×10^{-3}	2.429	2024.04
B30/0.35	0.2	0.1	0.06	1.2×10^{-3}	2.465	2054.17
	0.2	0.1	0.06	1.2×10^{-3}	2.440	2033.33
	0.2	0.1	0.06	1.2×10^{-3}	2.472	2060.00
	0.2	0.1	0.06	1.2×10^{-3}	2.457	2047.03
	0.2	0.1	0.06	1.2×10^{-3}	2.447	2039.17
	Mean			1.2×10^{-3}	2.456	2046.74
B40/0.20	0.2	0.1	0.06	1.2×10^{-3}	2.307	1922.50
	0.2	0.1	0.06	1.2×10^{-3}	2.294	1911.59
	0.2	0.1	0.06	1.2×10^{-3}	2.305	1920.83
	0.2	0.1	0.06	1.2×10^{-3}	2.277	1897.50
	0.2	0.1	0.06	1.2×10^{-3}	2.275	1895.83
	Mean			1.2×10^{-3}	2.291	1909.65
B40/0.25	0.2	0.1	0.06	1.2×10^{-3}	2.334	1945.00
	0.2	0.1	0.06	1.2×10^{-3}	2.309	1924.17

Continuation of B1

Batch	Dimensions of specimen			Volume(V) (m^3)	Weight(M) (kg)	Density(M/V) (kg/m^3)
	Length(m)	Width(m)	Height(m)			
B40/0.25	0.2	0.1	0.06	1.2×10^{-3}	2.329	1940.83
	0.2	0.1	0.06	1.2×10^{-3}	2.318	1931.75
	0.2	0.1	0.06	1.2×10^{-3}	2.304	1920.00
	Mean			1.2×10^{-3}	2.319	1932.35
B40/0.30	0.2	0.1	0.06	1.2×10^{-3}	2.329	1940.83
	0.2	0.1	0.06	1.2×10^{-3}	2.338	1948.83
	0.2	0.1	0.06	1.2×10^{-3}	2.363	1969.17
	0.2	0.1	0.06	1.2×10^{-3}	2.354	1961.67
	0.2	0.1	0.06	1.2×10^{-3}	2.346	1955.25
	Mean			1.2×10^{-3}	2.346	1955.05
B40/0.35	0.2	0.1	0.06	1.2×10^{-3}	2.389	1990.83
	0.2	0.1	0.06	1.2×10^{-3}	2.374	1978.80
	0.2	0.1	0.06	1.2×10^{-3}	2.361	1967.50
	0.2	0.1	0.06	1.2×10^{-3}	2.385	1987.50
	0.2	0.1	0.06	1.2×10^{-3}	2.357	1964.17
	Mean			1.2×10^{-3}	2.373	1977.76
B50/0.20	0.2	0.1	0.06	1.2×10^{-3}	2.228	1856.67
	0.2	0.1	0.06	1.2×10^{-3}	2.196	1830.00
	0.2	0.1	0.06	1.2×10^{-3}	2.222	1851.67
	0.2	0.1	0.06	1.2×10^{-3}	2.208	1840.01
	0.2	0.1	0.06	1.2×10^{-3}	2.190	1825.00
	Mean			1.2×10^{-3}	2.209	1840.67
B50/0.25	0.2	0.1	0.06	1.2×10^{-3}	2.256	1880.00
	0.2	0.1	0.06	1.2×10^{-3}	2.236	1863.53
	0.2	0.1	0.06	1.2×10^{-3}	2.224	1853.33
	0.2	0.1	0.06	1.2×10^{-3}	2.248	1873.33
	0.2	0.1	0.06	1.2×10^{-3}	2.216	1846.67
	Mean			1.2×10^{-3}	2.236	1863.37
B50/0.30	0.2	0.1	0.06	1.2×10^{-3}	2.282	1901.67
	0.2	0.1	0.06	1.2×10^{-3}	2.250	1875.00
	0.2	0.1	0.06	1.2×10^{-3}	2.260	1883.68
	0.2	0.1	0.06	1.2×10^{-3}	2.278	1898.33
	0.2	0.1	0.06	1.2×10^{-3}	2.246	1871.67
	Mean			1.2×10^{-3}	2.264	1886.07
B50/0.35	0.2	0.1	0.06	1.2×10^{-3}	2.273	1894.17
	0.2	0.1	0.06	1.2×10^{-3}	2.302	1918.33

Continuation of B1

Batch	Dimensions of specimen			Volume(V) (m^3)	Weight(M) (kg)	Density(M/V) (kg/m^3
	Length(m)	Width(m)	Height(m)			
B50/0.35	0.2	0.1	0.06	1.2 x 10^{-3}	2.292	1910.57
	0.2	0.1	0.06	1.2 x 10^{-3}	2.278	1898.33
	0.2	0.1	0.06	1.2 x 10^{-3}	2.307	1922.50
	Mean			1.2 x 10^{-3}	2.290	1908.78
B60/0.20	0.2	0.1	0.06	1.2 x 10^{-3}	2.144	1786.67
	0.2	0.1	0.06	1.2 x 10^{-3}	2.126	1771.78
	0.2	0.1	0.06	1.2 x 10^{-3}	2.113	1760.83
	0.2	0.1	0.06	1.2 x 10^{-3}	2.139	1782.50
	0.2	0.1	0.06	1.2 x 10^{-3}	2.108	1756.67
	Mean			1.2 x 10^{-3}	2.126	1771.69
B60/0.25	0.2	0.1	0.06	1.2 x 10^{-3}	2.167	1805.83
	0.2	0.1	0.06	1.2 x 10^{-3}	2.134	1778.33
	0.2	0.1	0.06	1.2 x 10^{-3}	2.173	1810.83
	0.2	0.1	0.06	1.2 x 10^{-3}	2.154	1794.46
	0.2	0.1	0.06	1.2 x 10^{-3}	2.139	178.50
	Mean			1.2 x 10^{-3}	2.153	1794.39
B60/0.30	0.2	0.1	0.06	1.2 x 10^{-3}	2.168	1806.67
	0.2	0.1	0.06	1.2 x 10^{-3}	2.179	1815.50
	0.2	0.1	0.06	1.2 x 10^{-3}	2.198	1831.67
	0.2	0.1	0.06	1.2 x 10^{-3}	2164	1803.33
	0.2	0.1	0.06	1.2 x 10^{-3}	2.194	1828.33
	Mean			1.2 x 10^{-3}	2.181	1817.10
B60/0.35	0.2	0.1	0.06	1.2 x 10^{-3}	2.225	1854.17
	0.2	0.1	0.06	1.2 x 10^{-3}	2.192	1826.67
	0.2	0.1	0.06	1.2 x 10^{-3}	2.222	1851.67
	0.2	0.1	0.06	1.2 x 10^{-3}	2.210	1842.32
	0.2	0.1	0.06	1.2 x 10^{-3}	2.189	1824.17
	Mean			1.2 x 10^{-3}	2.207	1839.80

B2: Water absorption test results

Batch	Mass of specimen before immersion (M_1) (kg)	Mass of specimen after immersion (M_2) (kg)	Water absorption (%) = [(M2 – M1)/M1] x 100
A0.35	2.799	2.840	1.44
	2.779	2.820	
	2.767	2.808	
	2.793	2.832	
	2.761	2.799	
Mean	2.780	2.820	
B10/0.35	2.678	2.718	1.50
	2.646	2.687	
	2.674	2.713	
	2.659	2.700	
	2.642	2.683	
Mean	2.660	2.700	
B20/0.35	2.563	2.635	1.55
	2.579	2.619	
	2.592	2.630	
	2.568	2.610	
	2.597	2.605	
Mean	2.580	2.620	
B30/0.35	2.371	2.410	1.59
	2.402	2.439	
	2.376	2.415	
	2.388	2.428	
	2.407	2.444	
Mean	2.389	2.427	
B40/0.35	2.355	2.396	1.64
	2.374	2.412	
	2.388	2.428	
	2.360	2.398	
	2.393	2.430	
Mean	2.374	2.413	
B50/0.35	2.309	2.348	1.70
	2.279	2.318	
	2.305	2.344	
	2.291	2.330	
	2.275	2.314	
Mean	2.292	2.331	

Continuation of B2

Batch	Mass of specimen before immersion (M_1) (kg)	Mass of specimen after immersion (M_2) (kg)	Water absorption (%) = [(M2 – M1)/M1] x 100
B60/0.35	2.225	2.264	1.76
	2.201	2.240	
	2.210	2.248	
	2.219	2.258	
	2.195	2.234	
Mean	2.210	2.249	

Appendix - C: Test results for mechanical properties of RCPBs

C1: 28 day compressive test results

Batch	Dimensions of specimen			Failure load (KN)	Compressive strength(N/mm^2)
	Length (mm)	Width (mm)	Height (mm)		
A0.20	200	100	60	343.4	17.17
	200	100	60	335.1	16.76
	200	100	60	357.2	17.86
	200	100	60	329.7	16.49
	200	100	60	364.6	18.23
	Mean			346.0	17.30
A0.25	200	100	60	445.8	22.29
	200	100	60	436.2	21.81
	200	100	60	459.4	22.97
	200	100	60	433.9	21.69
	200	100	60	464.7	23.24
	Mean			448.0	22.40
A0.30	200	100	60	523.4	26.17
	200	100	60	534.7	26.74
	200	100	60	512.1	25.61
	200	100	60	509.1	25.46
	200	100	60	530.7	26.54
	mean			522.0	26.10
A0.35	200	100	60	613.1	30.66
	200	100	60	602.8	30.14
	200	100	60	619.4	30.97
	200	100	60	595.3	29.76
	200	100	60	589.4	29.47
	Mean			604.0	30.20
B10/0.20	200	100	60	278.8	13.94
	200	100	60	286.5	14.33
	200	100	60	302.7	15.13
	200	100	60	297.9	14.90
	200	100	60	273.1	13.66
	Mean			287.8	14.39
B10/0.25	200	100	60	362.5	18.13
	200	100	60	374.5	18.72
	200	100	60	381.0	19.05
	200	100	60	383.8	19.19
	200	100	60	360.2	18.01
	Mean			372.4	18.62

Continuation of C1

Batch	Dimensions of specimen			Failure load (KN)	Compressive strength(N/mm^2)
	Length (mm)	Width (mm)	Height (mm)		
B10/0.30	200	100	60	431.3	21.56
	200	100	60	423.2	21.16
	200	100	60	443.6	22.18
	200	100	60	445.1	22.26
	200	100	60	418.8	20.94
	Mean			432.4	21.62
B10/0.35	200	100	60	501.7	25.09
	200	100	60	512.9	25.64
	200	100	60	495.3	24.77
	200	100	60	508.0	25.40
	200	100	60	492.1	24.61
	Mean			502.0	25.10
B20/0.20	200	100	60	221.5	11.08
	200	100	60	232.4	11.62
	200	100	60	214.7	10.74
	200	100	60	210.8	10.54
	200	100	60	238.6	11.93
	Mean			223.6	11.18
B20/0.25	200	100	60	288.3	14.41
	200	100	60	281.5	14.08
	200	100	60	297.4	14.87
	200	100	60	292.3	14.62
	200	100	60	287.5	14.38
	Mean			289.4	14.47
B20/0.30	200	100	60	346.8	17.34
	200	100	60	335.2	16.76
	200	100	60	327.2	16.36
	200	100	60	354.8	17.74
	200	100	60	321.0	16.05
	Mean			337.0	16.85
B20/0.35	200	100	60	383.0	19.15
	200	100	60	389.0	19.48
	200	100	60	398.8	19.94
	200	100	60	378.4	18.92
	200	100	60	400.3	20.02
	Mean			390.0	198.50

Continuation of C1

Batch	Dimensions of specimen			Failure load (KN)	Compressive strength(N/mm^2)
	Length (mm)	Width (mm)	Height (mm)		
B30/0.20	200	100	60	171.8	8.59
	200	100	60	183.4	9.17
	200	100	60	192.2	9.61
	200	100	60	169.3	8.47
	200	100	60	194.3	9.71
	Mean			182.2	9.11
B30/0.25	200	100	60	226.9	11.35
	200	100	60	234.6	11.73
	200	100	60	245.8	12.29
	200	100	60	217.9	10.90
	200	100	60	253.8	12.69
	Mean			235.8	11.79
B30/0.30	200	100	60	276.6	13.83
	200	100	60	265.9	13.29
	200	100	60	284.8	14.24
	200	100	60	257.9	12.90
	200	100	60	288.8	14.44
	Mean			274.8	13.74
B30/0.35	200	100	60	317.8	15.89
	200	100	60	329.2	16.46
	200	100	60	310.1	15.51
	200	100	60	301.2	15.06
	200	100	60	331.7	16.59
	Mean			318.0	15.90
B40/0.20	200	100	60	123.7	6.19
	200	100	60	135.8	6.79
	200	100	60	112.2	5.61
	200	100	60	131.6	6.58
	200	100	60	106.4	5.32
	Mean			122.0	6.10
B40/0.25	200	100	60	158.6	7.93
	200	100	60	167.8	8.39
	200	100	60	149.0	7.45
	200	100	60	143.8	7.19
	200	100	60	169.7	8.48
	Mean			157.8	7.89

Continuation of C1

Batch	Dimensions of specimen			Failure load (KN)	Compressive strength(N/mm^2)
	Length (mm)	Width (mm)	Height (mm)		
B40/0.30	200	100	60	184.3	9.22
	200	100	60	173.2	8.66
	200	100	60	197.9	9.90
	200	100	60	168.1	8.41
	200	100	60	192.5	9.63
	Mean			183.2	9.16
B40/0.35	200	100	60	201.2	10.06
	200	100	60	213.4	10.67
	200	100	60	223.5	11.18
	200	100	60	197.0	9.85
	200	100	60	224.9	11.25
	Mean			202.0	10.60
B50/0.20	200	100	60	73.4	3.67
	200	100	60	65.8	3.29
	200	100	60	80.1	4.01
	200	100	60	66.0	3.30
	200	100	60	77.7	3.88
	Mean			72.6	3.63
B50/0.25	200	100	60	92.3	4.62
	200	100	60	89.1	4.46
	200	100	60	97.8	4.89
	200	100	60	103.9	5.20
	200	100	60	85.9	4.30
	Mean			93.8	4.69
B50/0.30	200	100	60	110.7	5.54
	200	100	60	101.2	5.06
	200	100	60	115.4	5.77
	200	100	60	96.0	4.80
	200	100	60	120.7	6.03
	Mean			108.8	5.44
B50/0.35	200	100	60	125.2	6.26
	200	100	60	131.0	6.55
	200	100	60	122.1	6.11
	200	100	60	116.2	5.81
	200	100	60	135.5	6.77
	Mean			126.0	6.30

Continuation of C1

Batch	Dimensions of specimen			Failure load (KN)	Compressive strength(N/mm^2)
	Length (mm)	Width (mm)	Height (mm)		
B60/0.20	200	100	60	48.1	2.41
	200	100	60	53.6	2.68
	200	100	60	45.8	2.29
	200	100	60	55.6	2.78
	200	100	60	44.9	2.24
	Mean			49.6	2.48
B60/0.25	200	100	60	63.8	3.19
	200	100	60	59.1	2.96
	200	100	60	67.1	3.36
	200	100	60	60.0	2.99
	200	100	60	70.0	3.50
	Mean			64.0	3.20
B60/0.30	200	100	60	73.8	3.69
	200	100	60	81.0	4.05
	200	100	60	71.1	3.56
	200	100	60	67.0	3.35
	200	100	60	77.1	3.86
	Mean			74.0	3.70
B60/0.35	200	100	60	89.1	4.46
	200	100	60	85.8	4.29
	200	100	60	78.0	3.90
	200	100	60	94.2	4.70
	200	100	60	83.1	4.16
	Mean			86.0	4.30

C2: Compressive strength test results for different curing ages

Batch	Dimensions of specimen (mm)			Failure load (KN)			Compressive strength (N/mm^2)		
	length	width	Height	7 days	14days	28days	7 days	14days	28days
A0.35	200	100	60	441.1	559.6	593.1	22.06	27.98	29.66
	200	100	60	432.2	530.6	614.3	21.61	26.53	30.71
	200	100	60	450.3	533.7	605.0	22.51	26.68	30.25
	200	100	60	452.4	542.5	590.2	22.62	27.13	29.51
	200	100	60	489.0	551.6	617.4	24.45	27.58	30.87
	Mean			453.0	543.6	604.0	22.65	27.18	30.20
B10/0.35	200	100	60	361.4	439.4	500.5	18.07	21.97	25.03
	200	100	60	353.5	438.2	493.2	17.67	21.91	24.66
	200	100	60	372.4	461.8	512.8	18.62	23.09	25.64
	200	100	60	393.1	443.0	489.1	19.66	22.15	24.45
	200	100	60	376.6	451.6	514.4	18.83	22.58	25.72
	Mean			371.4	446.8	502.0	18.57	22.34	25.10
B20/0.35	200	100	60	283.2	324.6	390.5	14.16	16.23	19.52
	200	100	60	275.6	337.1	381.2	13.78	16.85	19.06
	200	100	60	293.4	342.3	402.1	14.67	17.12	20.11
	200	100	60	271.1	361.8	376.8	13.56	18.09	18.84
	200	100	60	299.7	350.2	399.4	14.99	17.51	19.97
	Mean			284.6	343.2	390.0	14.23	17.16	19.50
B30/0.35	200	100	60	230.8	301.0	318.3	11.54	15.05	15.92
	200	100	60	241.9	271.2	327.1	12.09	13.56	16.35
	200	100	60	223.1	277.4	308.8	11.16	13.87	15.44
	200	100	60	251.9	296.0	305.7	12.60	14.80	15.29
	200	100	60	244.3	285.4	330.1	12.22	14.27	16.51
	Mean			238.4	286.2	318.0	11.92	14.31	15.90
B40/0.35	200	100	60	153.3	197.5	211.5	7.67	9.87	10.57
	200	100	60	144.8	182.8	202.4	7.24	8.14	10.12
	200	100	60	162.1	188.1	223.1	8.11	9.41	11.16
	200	100	60	154.5	183.4	200.9	7.73	9.17	10.05
	200	100	60	169.3	191.2	222.1	8.47	9.56	11.11
	Mean			156.8	188.6	212.0	7.84	9.43	10.60
B50/0.35	200	100	60	89.1	110.6	125.3	4.46	5.53	6.26
	200	100	60	94.8	103.1	120.5	4.74	5.16	6.03
	200	100	60	85.2	119.3	133.4	4.26	6.02	6.67
	200	100	60	92.0	107.4	115.4	4.60	5.37	5.77
	200	100	60	98.9	113.6	135.4	5.01	5.68	6.77
	Mean			92.0	110.8	126.0	4.60	5.54	6.30

Continuation of C2

Batch	Dimensions of specimen (mm)			Failure load (KN)			Compressive strength (N/mm^2)		
	Length	Width	Height	7 days	14days	28days	7 days	14ays	28days
B60/0.35	200	100	60	72.6	83.3	96.3	3.63	4.16	4.82
	200	100	60	59.0	68.2	77.3	2.95	3.41	3.86
	200	100	60	55.8	74.2	98.5	2.79	3.71	4.93
	200	100	60	67.1	85.1	72.0	3.36	4.26	3.60
	200	100	60	62.5	76.3	85.9	3.12	3.82	4.29
	Mean			63.4	77.4	86.0	3.17	3.87	4.30

C4: Splitting tensile strength test results for different curing ages

Batch	Dimensions of specimen (mm)			Failure load (KN)			Splitting tensile strength (N/mm^2)		
	Length	Width	Height	7 days	14days	28days	7 days	14days	28days
A0.35	200	100	60	46.2	57.2	65.2	2.90	3.59	4.09
	200	100	60	48.3	53.4	58.6	3.03	3.35	3.67
	200	100	60	42.5	55.1	67.9	2.67	3.45	4.26
	200	100	60	40.4	62.6	57.8	2.54	3.93	3.63
	200	100	60	49.6	52.7	62.5	3.11	3.31	3.92
	Mean			45.4	56.2	62.4	2.85	3.53	3.92
B10/0.35	200	100	60	46.4	56.3	57.4	2.91	3.53	3.60
	200	100	60	41.5	51.6	61.6	2.61	3.24	3.87
	200	100	60	44.4	49.7	55.5	2.78	3.12	3.48
	200	100	60	35.9	55.3	52.5	2.25	3.47	3.29
	200	100	60	39.8	46.6	65.0	2.50	2.93	4.08
	Mean			41.6	51.9	58.4	2.61	3.26	3.67
B20/0.35	200	100	60	43.2	42.9	51.5	2.71	2.69	3.23
	200	100	60	35.9	41.0	48.7	2.25	2.57	3.06
	200	100	60	33.8	38.0	42.8	2.12	2.39	268
	200	100	60	39.4	45.5	46.9	2.47	2.86	2.94
	200	100	60	30.7	46.6	53.6	1.93	2.93	3.37
	Mean			36.6	42.8	48.7	2.30	2.69	3.06
B30/0.35	200	100	60	29.3	39.8	41.3	1.84	2.50	2.59
	200	100	60	32.1	31.5	43.6	2.02	1.98	2.74
	200	100	60	26.2	42.7	34.9	1.64	2.68	2.19
	200	100	60	23.5	33.4	46.7	1.48	2.10	2.93
	200	100	60	34.4	35.6	37.5	2.16	2.23	2.35
	Mean			29.1	36.6	40.8	1.83	2.30	2.56

Continuation of C4

Batch	Dimensions of specimen (mm)			Failure load (KN)			Splitting tensile strength (N/mm^2)		
	Length	Width	Height	7 days	14days	28days	7 days	14days	28days
B40/0.35	200	100	60	23.3	31.2	28.7	1.46	1.96	1.80
	200	100	60	25.9	27.9	30.8	1.63	1.75	1.93
	200	100	60	18.5	22.8	37.2	1.16	1.43	2.34
	200	100	60	20.4	25.2	26.5	1.28	1.58	1.66
	200	100	60	27.4	32.9	34.3	1.72	2.07	2.15
	Mean			23.1	28.0	31.5	1.45	1.76	1.98
B50/0.35	200	100	60	17.3	20.1	21.3	1.09	1.26	1.33
	200	100	60	13.9	19.2	17.8	0.87	1.21	1.12
	200	100	60	12.5	18.8	21.5	0.78	1.18	1.32
	200	100	60	14.2	16.4	23.3	0.89	1.03	1.46
	200	100	60	14.3	15.5	19.1	0.90	0.97	1.20
	Mean			14.5	18.0	20.5	0.91	1.13	1.29
B60/0.35	200	100	60	12.6	13.3	17.5	0.79	0.84	1.10
	200	100	60	13.4	10.8	12.5	0.84	0.68	0.78
	200	100	60	10.9	14.9	16.8	0.68	0.94	1.05
	200	100	60	9.6	16.6	14.3	0.60	1.04	0.90
	200	100	60	11.5	13.9	16.4	0.72	0.87	1.03
	Mean			11.6	13.9	15.5	0.73	0.87	0.97

C4: Flexural strength test results for different curing ages

Batch	Dimensions of specimen (mm)			Failure load (KN)			Flexural strength (N/mm^2)		
	Length	Width	Height	7 days	14days	28days	7 days	14days	28days
A0.35	200	100	60	4.7	5.8	7.2	2.94	3.63	4.50
	200	100	60	5.3	6.5	6.7	3.31	4.06	4.18
	200	100	60	5.5	5.5	6.5	3.44	3.44	4.06
	200	100	60	4.4	5.9	7.0	2.75	3.68	4.38
	200	100	60	5.1	6.3	6.1	3.19	3.94	3.81
	Mean			5.0	6.0	6.7	3.13	3.75	4.18
B10/0.35	200	100	60	4.4	6.0	5.9	2.75	3.75	3.68
	200	100	60	4.9	5.8	6.6	3.06	3.63	4.13
	200	100	60	5.1	5.2	6.4	3.19	3.25	4.00
	200	100	60	4.5	4.9	5.6	2.81	3.06	3.50
	200	100	60	4.1	5.6	6.0	2.56	3.50	3.75
	Mean			4.6	5.5	6.1	2.84	3.43	3.81

Continuation of C4

Batch	Dimensions of specimen (mm)			Failure load (KN)			Flexural strength (N/mm^2)		
	Length	Width	Height	7 days	14days	28days	7days	14days	28days
	200	100	60	3.9	4.5	5.4	2.43	2.81	3.38
	200	100	60	4.6	4.9	5.2	2.87	3.06	3.25
B20/0.35	200	100	60	4.3	5.1	4.9	2.69	3.19	3.06
	200	100	60	3.5	4.3	5.6	2.18	2.69	3.50
	200	100	60	3.7	5.2	5.9	2.31	3.25	3.69
	Mean			4.0	4.8	5.4	2.49	3.00	3.35
	200	100	60	3.3	4.7	5.2	2.06	2.94	3.20
	200	100	60	3.7	4.1	4.2	2.31	2.56	2.63
B30/0.35	200	100	60	2.9	3.9	4.9	1.81	2.43	3.06
	200	100	60	3.2	4.3	4.2	2.00	2.69	2.63
	200	100	60	3.9	3.5	4.5	2.44	2.18	2.81
	Mean			3.4	4.1	4.6	2.12	2.56	2.86
	200	100	60	2.9	2.7	3.5	1.81	1.69	2.19
	200	100	60	2.7	3.5	4.1	1.69	2.19	2.56
B40/0.35	200	100	60	3.1	3.0	3.1	1.94	1.88	1.94
	200	100	60	2.3	3.6	3.4	1.44	2.25	2.13
	200	100	60	2.0	3.2	3.9	1.25	2.00	2.44
	Mean			2.6	3.2	3.6	1.64	2.00	2.21
	200	100	60	2.0	2.8	2.9	1.25	1.75	1.81
	200	100	60	2.3	3.0	3.3	1.44	1.87	2.06
B50/0.35	200	100	60	1.7	2.1	3.1	1.06	1.31	1.94
	200	100	60	2.5	2.4	2.3	1.56	1.50	1.44
	200	100	60	1.5	2.2	2.4	0.94	1.38	1.50
	Mean			2.0	2.5	2.8	1.28	1.56	1.71
	200	100	60	1.5	1.7	1.6	0.94	1.06	1.00
	200	100	60	1.9	2.2	2.3	1.19	1.38	1.44
B60/0.35	200	100	60	1.3	2.0	1.7	0.81	1.25	1.06
	200	100	60	1.1	1.6	2.5	0.69	1.00	1.56
	200	100	60	1.7	1.5	1.9	1.06	0.94	1.19
	Mean			1.5	1.8	2.0	0.94	1.13	1.28