ENGINEERING CHARACTERISTICS OF MODIFIED ROLLER-COMPACTED CONCRETE PAVEMENT

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ENGINEERING CHARACTERISTICS OF MODIFIED ROLLER-COMPACTED CONCRETE PAVEMENT

ABSTRACT

In order to investigate new characteristics of roller-compacted concrete pavement (RCCP), the first part of the study dealt with the analysis of fresh and hardened properties of RCCP subjected to applying different coarse to fine aggregate (C/F) ratio, the use of low fines content sand and study on optimum moisture content in RCCP production. Test results showed that the most suitable C/F ratio for RCCP may appear to be from 1.2 to 1.4. The use of low fines content sand in RCCP for both cement contents of 12% and 15% did not significantly affect the mechanical properties of RCCP at all ages. In addition, the study on optimum moisture content of RCCP concluded that a workable, high-strength, and durable RCCP can be made with a moisture content less than the optimum moisture content, which is corresponding to the maximum dry density. In the second part of the study, a comprehensive numerical comparison between normal vibrated concrete (NVC) and RCCP was presented. Test results showed that mechanical properties of RCCP was higher than that of NVC. Durability performance of RCCP is also better than NVC at the same mix proportions. The effect of using different amount of superplasticizer on the fresh and hardened properties of two RCCPs with cement contents of 12% and 15% showed that with the use of superplasticizer, the 28-day compressive strength for RCCP containing 12% and 15% cement increased by 9% and 14%, respectively. Also, Ultrasonic pulse velocity, field emission scanning electron microscope and thermal conductivity test results showed that the use of superplasticizer in RCCP may lead to denser structure. Finally, the results of experimental program showed that the incorporation of lightweight expanded clay aggregate (LECA) by 50% as coarse aggregate in RCCPs with 12% and 15% cement contents can cause 15% and 13% lesser density, 9% and 13% higher

workability, respectively, with suitable results in terms of hardened properties and durability.

Keywords: roller-compacted concrete pavement, aggregate gradation, optimum moisture content, superplasticizer, lightweight expanded clay aggregate

CIRI-CIRI KEJURUTERAAN TURAPAN KONKRIT PENGGULUNG-MAMPATAN TERUBAHSUAI

ABSTRAK

Untuk menyiasat ciri-ciri baru RCCP, bahagian pertama kajian ini mengendalikan analisis sifat-sifat segar dan terkeras RCCP tertakluk kepada penggunaan nisbah kasar kepada agregat halus (C/F) yang berbeza, penggunaan kandungan-rendah-halus pasir dan mengkaji kandungan lembapan optimum di dalam pengeluaran RCCP. Keputusan ujian menunjukkan bahawa nisbah C/F yang paling sesuai untuk RCCP adalah di antara 1.2 hingga 1.4. Penggunaan kandungan-rendah-halus pasir dalam RCCP untuk kedua-dua kandungan simen iaitu 12% dan 15% tidak mempunyai kesan yang signifikan terhadap sifat-sifat mekanikal RCCP pada semua peringkat umur. Tambahan pula, kajian terhadap kandungan kelembapan optimum RCCP menyimpulkan bahawa RCCP yang mempunyai kebolehkerjaan, kekuatan tinggi dan ketahanan boleh dibuat dengan kandungan kelembapan yang kurang daripada kandungan kelembapan yang optimum, dengan merujuk kepada ketumpatan kering maksimum. Di dalam bahagian kedua kajian, perbandingan numerikal yang komprehensif di antara NVC dan RCCP telah dibentangkan. Keputusan ujian menunjukkan bahawa prestasi ketahanan RCCP lebih tinggi daripada NVC untuk kandungan campuran yang sama.Kesan penggunaan jumlah superpemplastik yang berbeza ke atas ciri-ciri segar dan terkeras untuk dua RCCP dengan kandungan simen iaitu 12% dan 15% menunjukkan bahawa dengan penggunaan superpemplastik, kekuatan kemampatan pada hari ke-28 ke atas RCCP yang mengandungi kandungan simen 12% dan 15% meningkat sebanyak 9% dan 14%.Begitu juga dengan halaju nadi Ultrasonik, Mikroskop Pengimbasan Pelepasan Medan dan hasil ujian kekonduksian terma menunjukkan bahawa penggunaan superpemplastik di dalam RCCP boleh menyebabkan struktur yang lebih padat. Akhirnya, keputusan eksperimen menunjukkan penggabungan Aggregat Tanah Liat Lanjutan Ringan (LECA) sebanyak 50% sebagai aggregat kasar di dalam RCCPs dengan kandungan simen sebanyak 12% dan 15% akan menyebabkan ketumpatan kurang kepada 15‰ dan 13%, kebolehkerjaan meningkat sebanyak 9‰ dan 13%, yang mana sesuai untuk ciri-ciri kekerasan dan ketahanan.

kata kunci: turapan konkrit penggulung-mampatan, penggredan aggregat, kandungan kelembapan optimum. superpemplastik, Aggregat Tanah Liat Lanjutan Ringan

DEDICATIONS

I dedicate this thesis to my wife and parents

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CHAPTER 1. INTRODUCTION

1.1 Research background

Concrete is the most common used material in construction of civil engineering projects all over the world because of the reasons like; It has perfect resistance to water, concrete structural elements are more formable and shapeable comparing with other materials and it is the cheapest material with highest availability for the job (Mehta, 2006). Annual production of more than 10 billion tons of concrete has made it the most important building material (Shafigh et al., 2014). From the various kinds of concrete, Roller-Compacted Concrete (RCC) is one of the most interesting concrete in comparison with other concrete because of its advantages. RCC is used for the construction of dams and pavements (Marchand et al., 1997).

RCC was widely first used in the construction of dams. The use of RCC in dam construction helped to ease construction and reduce heat of hydration (Harun, 2000). In the late 1970s, for first time the RCC technology has been used by the U.S. Army Corps of Engineers in the construction of Willow Creek Dam, in Oregon (Abdo, 2008). More than 370 RCC gravity and arch dams in excess of 50 feet in height have been constructed to date worldwide that forty-three of these dams are located in the United States (Paul & Slaven, 2009).

RCC technology was then applied to concrete pavement construction. For first time Roller compacted concrete pavement (RCCP) was performed in North America as airport runway in 1940 (Harrington et al., 2010). RCCP was used widely in Canada in 1976 for log storage area (Gauthier & Marchand, 2005).

Since early 1980s, the significant efforts and depth studies were carried out on RCCP by U.S. Army Corps of Engineers for military facilities. It was for first time that the U.S. Army Corps of Engineers tried to standardize the RCCP construction (Khayat & Libre, 2014). Later, RCCP was used mostly in the U.S for intermodal container terminals, storage yards, warehouse floors, intersections, and small roads (Hossain & Ozyildirim, 2015). Since early 2000s RCCP became known for constructing low to moderate traffic streets and secondary highways (Harrington et al., 2010). The use of RCCP has developed considerably in North America during the last decade, especially in the construction of low volume roads and parking lots (Pittman & Anderton, 2009). Presently, a significant number of off-highway pavement projects in the United States and Canada have been completed using RCCP technology (Khayat & Libre, 2014). Figure 1.1 indicates the cumulative use of RCCP in United States from 1975 to 2013. Table 1.1 shows some projects in worldwide that have been built by RCCP.

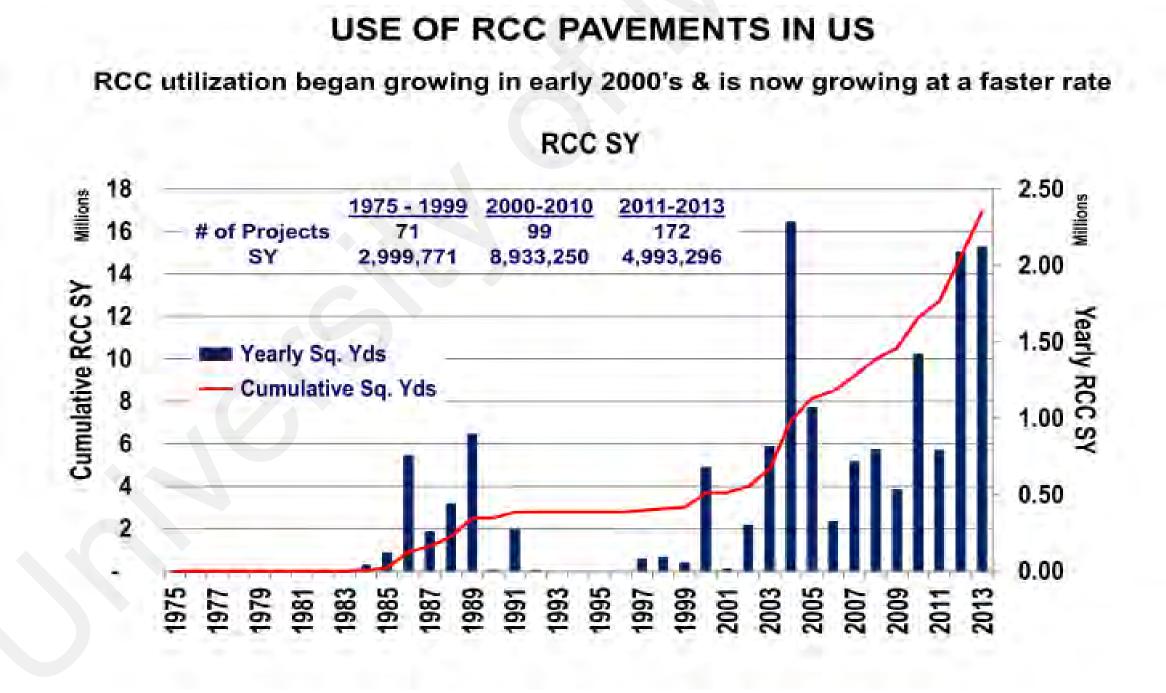

Figure 1.1: Cumulative use of RCCP in United States (Adaska, 2016)

Table 1.1: RCCP projects in Practice (Serne, 1997; Gauthier & Marchand, 2005; Gregory & Taylor, 2012; Corey & Zollinger, 2013)

Construction site	Year	Area (m^2)	Thickness (mm)
Coal storage area, British Columbia	1982	190000	225
Port of Tacoma South Intermodal Yard	1985	44300	460
Massachusetts Port Authority Conley Terminal	1986	63500	455
Saturn Corporation – Spring Hill, Tennessee	1988	545000	-
Athabasca, Alberta	1992	95000	250 - 300
Vancouver, British Columbia	1996	17000	425
Quebec, Domtar Paper mill wood lot in	1996	40000	300
Pier 300 Port of Los Angeles	1998	33400	430
Liverpool Port	2001	22000	300
Wanlip Sewerage Treatment Works	2003	40000	180
Virginia Port Authority	2004	46500	300 - 450
Green Waste Facility, Little Bushy warren Copse	2004	40000	200
Denver International Airport	2008	17441	200
Automotive plant, Volkswagen – Chattanooga, Tennessee	2010	418000	100
City of Streamwood Streets	2011	5000	152
Yuma east wetlands hike trail	2013	10000	127
Cross gate Road in Port Wentworth	2016	13400	254

In this study the focus is on the RCCP. RCCP is a stiffer concrete than conventional concrete in fresh state and it needs more compaction energy for consolidation. American Concrete Institute (ACI) defines RCCP as "concrete compacted by roller compaction that, in its unhardened state, will support a roller while being compacted" (Harrington et al., 2010; Jiang et al., 2013). RCCP gets its name from the method that is used to build it. Usually an asphalt paver with standard or high density screed is used for placement of RCCP and then the rollers for its compaction. The load carrying capacity of a RCCP is due to the compaction process to create friction between the particles or aggregate interlock.

RCCP is a kind of rigid pavement which has low water demand, low cement dosage, needs no forms or finishing, and there are no dowels, tie rods, or steel reinforcement (Liu et al., 2014; Harrington et al., 2010). It supports heavy, repetitive loads without failure, eliminates rutting and subsequent repairs, provides excellent durability even under freeze-thaw conditions and reduces permeability, and enhances resistance to chemical attack. Moreover, its light color reduces lighting requirements for parking and storage areas. These characteristics of RCCP result in simple, fast and affordable construction. However, for RCCP some limitations have been reported. According to most laboratory data, RCCP appears to be more susceptible to deicing salt-scaling than conventional Portland cement concrete mixtures of the same compressive strength (Khayat & Libre, 2014). Also, RCCP is not as pretty and smooth as conventional concrete and rougher surface texture and it is limited to low-speed traffic.

1.2 Problem statement

RCCP characteristics is highly affected by properties of its materials. Although, there are some guidelines to select the correct materials for RCCP, the modification on the mixture ingredients is still in need to be investigated. Almost all researchers emphasize on the observance of some limitations and restrictions in RCCP production such as aggregate gradation, specific content of fine particles passing from sieve #200 (75µm) and finding optimum moisture content, which lead to time-consuming and expensive construction. However, the data are insufficient and limited. Also, the effect of these limitations in RCCP production has not investigated comprehensively.

On the other hand, RCCP involves different placement and design considerations as compared to normal vibrated concrete. In addition, there are limited numerical data to compare difference properties of RCCP and normal vibrated concrete. Therefore, establishing the comparative evaluation criteria is necessary. In addition, although many years has passed since the first use of superplasticizers in concrete, however, information about the use of superplasticizers in RCCP is still limited. Therefore, more research need to be carried out in order to produce good quality and durable RCCP with superplasticizer. Finally, a review on literature showed that there is not detail information regarding to use of lightweight aggregate in RCCP. Therefore, investigation of the possibility of using lightweight aggregate as normal weight coarse aggregate replacement in RCCP due to reduced dead load of concrete seems to be important.

1.3 Research gap

Suitable aggregate gradation and correct selection of C/F ratio are the key influencing factors to make a good RCCP mixture in terms of workability, compactability, minimizing the voids in the cement matrix and reducing segregation as well as the surface finishes. The range of C/F ratio which is proposed by previous studies is very wide and is not applicable for selecting RCCP mix proportions. In addition, according to the previous studies, the percentage of fine particles passing through sieve #200 and sieve #100 have limited to 2-8% and 6-18%, respectively, for sand used in RCCP. However, there is no study to show the fresh and mechanical properties of RCCP in the absence of using low fine particles. The potential improvements in RCCP associated with the properties of fresh and hardened concrete at moisture content lower than optimum moisture content, which is corresponded to maximum dry density is not investigated comprehensively.

RCCP has the same ingredients (in different ratios) as NVC, however, limited numerical data on the differences between NVC and RCCP has been reported which may not be sufficient to draw conclusion. It should be noted that chemical admixtures such as superplasticizer, air entraining agents and retarders are commonly used in NVC. However, there is a conflict among researchers about the use of superplasticizer in RCCP due to low water content used in RCCP production. Finally, lightweight aggregates have been used in concrete pavement. However, there is no detail information regarding to use of lightweight aggregate in RCCP.

1.4 Objectives

The main objective of this research is to modify characteristics of RCCP to achieve and engineered economical pavement. The sub-objectives of this research are as following:

i. To study the effect of volume of coarse aggregate on the fresh and hardened properties of RCCP
ii. To investigate the effect of sand gradation on the fresh and hardened properties of RCCP
iii. To optimize the water content in RCCP
iv. To compare the mechanical properties of NVC and RCCP
v. To study the effectiveness of using superplasticizer on fresh and hardened properties of RCCP
vi. To investigate the effect of Lightweight Expanded Clay Aggregates (LECA) on the fresh and hardened properties and durability of RCCP

1.5 Scope of research

The first part of the research deals with the role of aggregate gradation and water content on the fresh and hardened properties of RCCP. RCCP as a zero-slump concrete, has lower cement content than conventional vibrated concrete. Therefore, the quality of the aggregates has a significant impact on the properties of concrete. For this reason, the quantity of coarse and fine aggregates in RCCP should be optimized. In this way the effect of coarse to fine aggregate ratio from 0.6 to 1.8, on the fresh and hardened properties of two RCCPs with cement contents of 9% and 12% was explored through the investigation of the mechanical and some durability-related properties. In addition, for manufacturing RCCP, there are some limitations for gradation of coarse and fine aggregates from the standards. Based on the ACI 211.3R-02, the content of sand size finer than 75 micrometres should be between 2 to 8% of the total aggregates. To study the effectiveness of using a sand which is out of the specified restriction on the properties of RCCP, three type of sands with different content of very fine particles (sand size finer than 75 micrometre) were used and the possibility of using low fines content sand was investigated. The maximum density method, having optimum moisture content at maximum dry density, is most commonly used for the mix proportioning of RCCP. However, the potential improvements in RCCP associated with the properties of fresh and hardened concrete at moisture content lower than optimum moisture content, which is corresponded to maximum dry density was investigated.

The second part of study involves a comparison between RCCP and normal vibrated concrete and feasibility of using superplasticizer and lightweight aggregate in RCCP production. The differences between RCCP and normal vibrated concrete in terms of fresh properties and hardened strengths such as compressive, splitting tensile and flexural strengths and modulus of elasticity, durability and thermal properties were assessed. Furthermore, Field Emission Scanning Electron Microscope (FESEM) was applied to assess microstructure of specimens. Superplasticizers is one of the most important ingredients used in concrete. Limited data on the use of superplasticizer in RCCP has been reported which may not be sufficient to draw conclusion. In the most previous studies, the use of superplasticizer in RCCP is not recommended due to lower water content used in RCCP production. The effect of using different amounts of superplasticizer (0.25% and 0.50%) on the fresh and hardened properties of two RCCPs with cement contents of 12% (269 kg/m3) and 15% (325 kg/m3) were investigated. Lightweight aggregate concrete has been successfully used for a number of applications for decades. However, a review on literature showed that there is not detail information regarding to use of lightweight aggregate in RCCP. Therefore, the possibility of using Lightweight Expanded Clay Aggregates (LECA) as normal weight coarse aggregate replacement with various dosages of 25, 50, 75 and 100% (by volume) in RCCP with 12% and 15% cement contents was explored.

1.6 Thesis overview

This thesis is divided into five main sections. The sections are, i) introduction; ii) literature review; iii) material characteristics and experimental program; iv) results and discussion v) conclusions and recommendations. The contents of each chapter are summarized as follows:

Chapter 1 Introduction

This chapter describes the background study and statement of problems leading up to the determination of the research objectives in this thesis. Based on the research objectives that were formed, the scope of research is also described in this chapter.

Chapter 2 Literature review

This chapter provides a brief literature review on RCCP materials selection and background on differences between RCCP and conventional concrete. It also gives a thorough review on the mixture proportioning methods for RCCP. Literature review was also carried out to discuss the behavior of RCCP in fresh and hardened states and the role of admixtures on its properties. Also, the use of waste and by-product materials in RCCP as cement replacement was discussed comprehensively.

Chapter 3 Material characteristics and experimental program

The properties of materials and their preparation before casting, mixture proportioning and test methods are presented in this chapter.

Chapter 4 Results and discussion

In this chapter, the experimental works are divided into six main parts. First, the role of coarse to fine aggregate ratio from 0.6 to 1.8, on the fresh and hardened properties of RCCP was investigated. Second, the effect and possibility of using low fines content sand in RCCP production was studied. Third, the potential improvements in fresh and hardened properties of RCCP at lower moisture content than optimum moisture content, corresponded to maximum dry density was explored. Fourth, a comprehensive numerical comparison between normal vibrated concrete and RCCP is presented and discussed. Fifth, the effect of using different amount of superplasticizer, i.e. 0.25% and 0.50%, on the fresh and hardened properties of two RCCPs mixes with cement contents of 12% and 15% was investigated. Finally, the influence of LECA substitution (in various dosage of 25, 50, 75 and 100%) as coarse aggregate on the fresh and hardened properties of RCCP and its durability was investigated.

Chapter 5 Conclusions and recommendations

This chapter states the summary and conclusions of the research work carried out and suggests the directions for future research.

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CHAPTER 2. LITERATURE REVIEW

This chapter revised the related findings from the literature review. The related literature review includes the previous finding on the behavior of RCCP in fresh and hardened states. Also, a comprehensive review on the material selection and mixture design methods is provided. Besides, the use of waste and by-product materials such as fly ash, coal bottom ash, ground granulated blast furnace slag and circulating fluidized bed combustion Ash as cement replacement in RCCP are also reported.

2.1 RCCP Materials selection

The correct selection of materials is the key parameter to get high quality RCCP. Although, RCCP contains the same ingredients as conventional concrete; cementitious materials, aggregates and water, but it has different mixture proportion. Generally, RCCP has more aggregate and lower binder content than conventional concrete of similar strength.

2.1.1 Cementitious materials

RCCP mixtures can be made with any of the basic types of hydraulic cement, blended cements, or a combination of hydraulic cement and pozzolan (Harrington et al., 2010). Cementitious materials should meet the requirements of ASTM C150 or ASTM C1157. The cement content in RCCP depends on, required workability, ultimate mechanical strength and durability criteria. Usually, RCCP contains lower cement content than conventional concrete. A study showed at compressive strength values of 45 MPa and 60 MPa, the binder dosage in RCCP mixes is respectively 20% and 28% less than for conventional concrete (Gauthier et al., 2000).

Generally, RCCP mixes are designed with cement contents ranging 12% to 16% of weight of total dry solids (Gauthier & Marchand, 2005). It is about 250 kg/m^3 to 350 kg/m^3. It should be noted, usually the ultimate mechanical strength can be reached between 11% and 13% (Khayat & Libre, 2014). Missouri Standard Specifications (2004) for Highway Construction requires that the total amount of cementitious materials shall not be below 240 kg/m^3.

The use of excessive cement in RCCP results in greater shrinkage cracking and significantly increase production costs (Gauthier & Marchand, 2005). However, in a low cement content mixture, there might be not sufficient paste to fill all the voids and the concrete may be subjected to segregation due to the low consistency (Khayat & Libre, 2014). The cementitious materials in RCCP mixture proportions computed using the following formula:

$$\text{Cementitious materials (\%)} = \frac{weight\ of\ \text{Cementitious materials}}{\text{Cementitious materials} + \text{Oven dried aggregate}} \qquad \text{(Eq.2.1)}$$

2.1.2 Aggregate

To produce high quality RCCP, both the coarse and fine aggregate fractions should be composed of hard, durable particles and the quality of each should be evaluated by standard physical property tests such as those listed in ASTM D3744-11 for concrete aggregates.

Aggregate content in RCCP is higher than conventional concrete. The aggregate content is typically between 75% to 85% from the total volume of RCCP. Meanwhile, the aggregate content for conventional concrete is 60% to 75% from its total volume (Alexander & Mindess, 2010; Burwell et al. 2014). RCCP in fresh state is significantly affected by aggregate properties considerably. Also, hardened strength, modulus of elasticity and durability of the RCCP are affected by the aggregate properties (Harrington et al., 2010; Khayat & Libre, 2014). Physical properties of aggregates;

moisture content and absorption characteristics and inherent properties of aggregates greatly affect RCCP in fresh state and its mechanical properties, respectively.

RCCP differs from conventional concrete in its aggregate gradation. It needs more aggregate skeleton in comparison with conventional concrete to be consolidated under compaction efforts. Aggregate gradation affects the compactability of RCCP and influence the minimum number of vibrating passes required for full consolidation (Harrington et al., 2010; Delatte, 2014). RCCP requires a similar aggregate grading to asphalt concrete mixtures because of the same method of placing and compaction (Pittman & White, 1985). Figure 2.1 shows different sizes of aggregate used in RCCP.

Figure 2.1: Aggregate grading in RCCP (Gauck et al., 2011)

Suitable aggregate gradation in RCCP can provide mixtures with sufficient workability and compactability and it also minimizes the voids, reduces the segregation and improve surface finish. The load carrying capacity of RCCP is due to the compaction process to create friction between the confined particles or aggregate interlock. A RCCP with the low cement content needs careful selection of the aggregate structure to ensure enough structural performance of the pavement (LaHucik & Roesler, 2015). Figure 2.2 shows the particle compaction in case of poorly graded and well graded aggregate and the relative quantity of cement that might be used. Load transfer significantly affects the performance of a concrete pavement. Poor load transfer may result in faulting, transverse cracking, and pumping, as well as reducing the service life of the pavement. Because RCCP is constructed without dowel bars, load transfer at its joints or cracks mainly depends on shear transfer capabilities induced by aggregate interlocks and base stiffness (Sok et al., 2018).

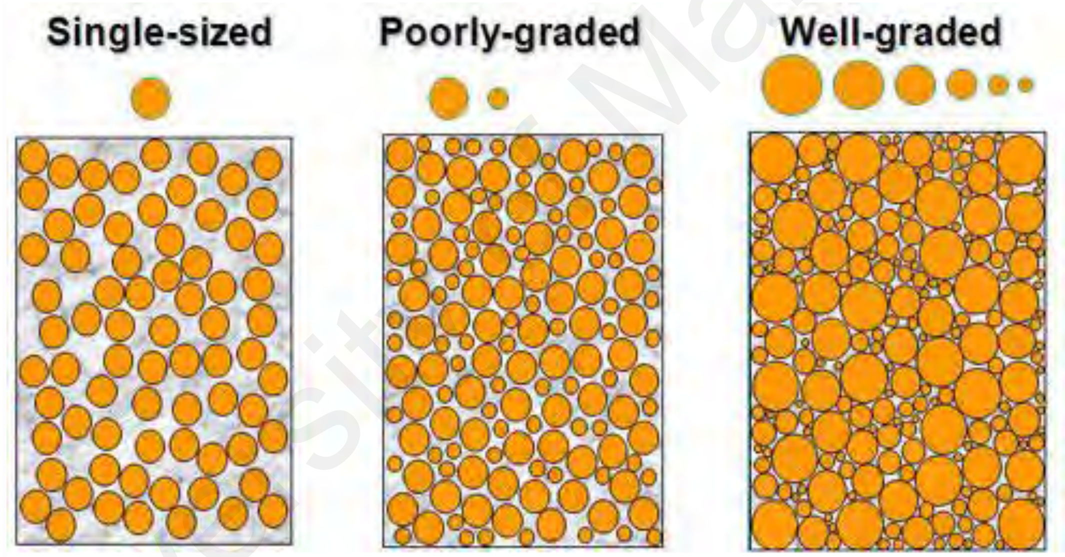


Figure 2.2: The role of well-graded aggregate in particle compaction (Awais, M. (2013, January 9). Gradation of Aggregates. Retrieved from http://engineeringlectures.com/gradation)

Similar aggregate gradation bands for RCCP were suggested by ACI and Portland Cement Association (PCA) which can be seen in Figure 2.3.

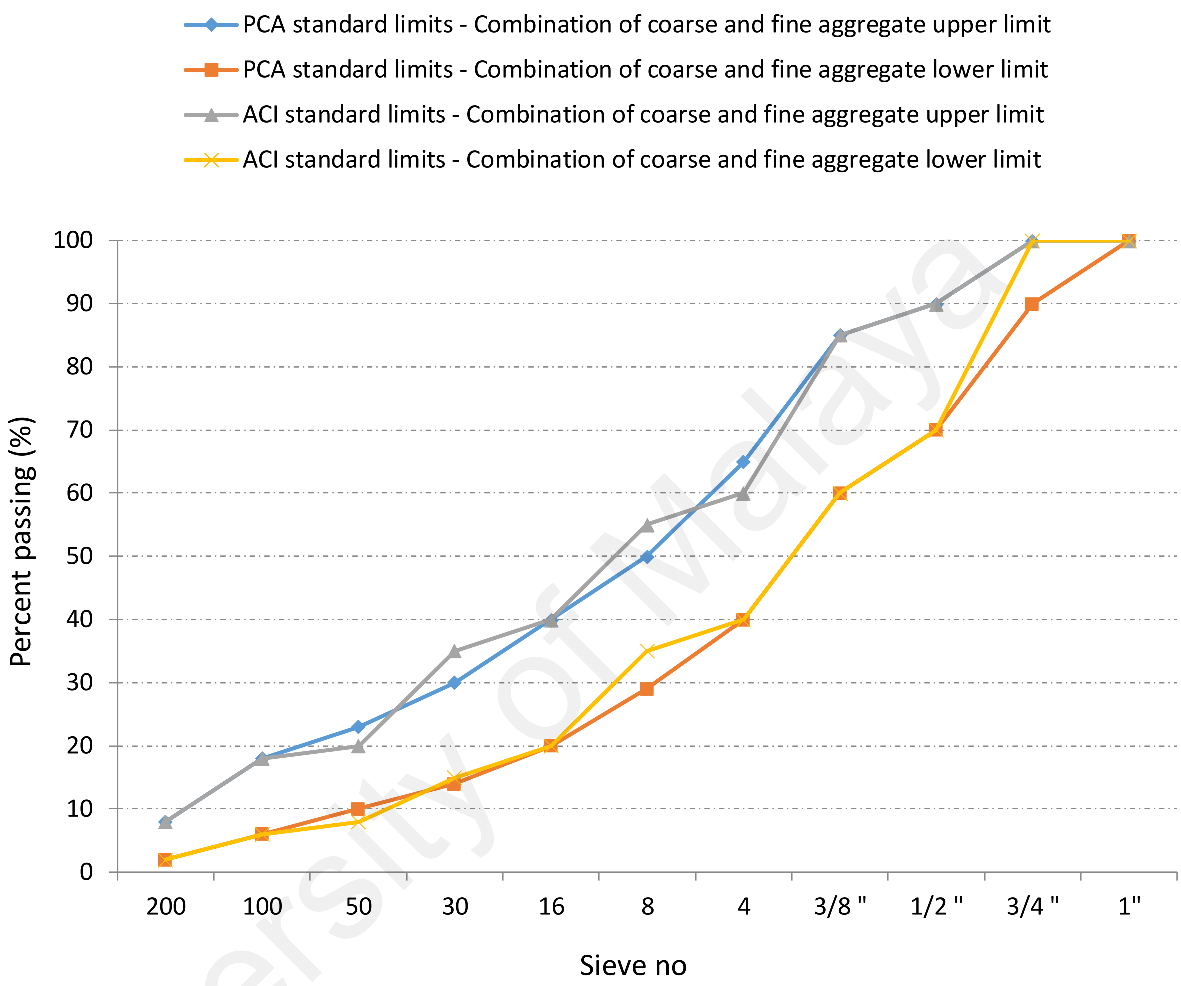


Figure 2.3: Suggested Limits for RCCP aggregate gradation by ACI and PCA

2.1.2.1 Coarse aggregate

Usually, coarse aggregates are limited to a nominal maximum size of aggregate (NMSA) of 19 mm to prevent segregation and achieve a tight surface (Palmer, 1987; ACI 325.10R-95; Marchand et al., 1997). Also, the NMSA is generally limited to 19 mm due to the tendency of large particles to produce more microcracks in the interfacial transition zone between the coarse aggregate and cement paste (Mehta, 2006). However, for multi-layer construction, aggregate with a maximum size of 40 mm (1 ½ in.) can be used for the first (i.e., bottom) layer (Canadian Portland Cement Association, 1997). It is recommended that NMSA should be smaller to improve riding quality (Gauthier & Marchand, 2005). Using a NMSA of 19 mm in RCCP mixture provides a better load transfer efficiency and is expected to improve the structural performance of RCCP (Sok et al., 2018).

Compared to RCCP containing naturally rounded gravel, RCCP containing crushed stone generally requires more water to attain a given consistency and more effort to compact. However, it is more stable during compaction and usually provides a higher flexural strength (ACI 325.10R-95).

2.1.2.2 Fine aggregate

The volume of fine aggregate smaller than 75-µm (fine aggregate passing through sieve #200) in RCCP mixture has significant role in this type of concrete at both fresh and hardened state (Harrington et al., 2010; Khayat & Libre, 2014). In order to improve the smoothness of the top surface of RCCP and to obtain a closed surface, it is recommended that non-plastic fines passing a 75-µm (No. 200) sieve be in the 5 to 10% range (Marchand et al., 1997; Palmer, 1987). However, ACI 325.10R-95 recommends fines content of 2 to 8%. It should be noted, NMSAs for coarse aggregate and, fine aggregate which passing from sieve #200 (75µm) are the critical parameters in RCCP (Harrington et al., 2010; Khayat & Libre, 2014; Engineers, 2000).

Some researchers reported that RCCP mixture often require a higher proportion of fine aggregate to coarse aggregate compared to conventional concrete that can result in a more homogenous mixture and reduce the risk of segregation (Harrington et al., 2010; Khayat & Libre, 2014; Canadian Portland Cement Association, 1997; US Departments of Army and Air Force, 1987; ACI 309.5R-00).

2.1.3 Water

Same requirement as for conventional concrete has been recommended for RCCP construction. Water quality is usually specified to meet the requirements of ASTM C1602-12. The water content (w) is usually expressed as a percentage (by weight) of the total solids in the mix:

$$\text{Water content (\%)} = \frac{weight\ of\ water\ in\ mix}{weight\ of\ oven{-}dry\ aggregates + cementitious\ material} \times 100 \qquad \text{(Eq.2.2)}$$

2.2 Differences between RCCP and NVC

ACI defines RCCP as “concrete compacted by roller compaction that, in its unhardened state, will support a roller while being compacted” (Jiang et al., 2013; U.S Department of Transportation., 2016). In NVC for different applications including concrete pavement, compaction is achieved through vibration generated by means of rotating eccentric having a frequency and amplitude pulse liquefy the mortar portion of concrete and thus reduce the internal friction resulting consolidation by force of gravity (Sudarshan & Chandrashekar,2017).

The differences between NVC and RCCP are tabulated in Table 2.1 below. The characteristics for each type of concrete are reviewed from various literatures. The differences in characteristics included the height of slump, mixture conditions, water/cement ratio, drying shrinkage and etc.

RCCP is a concrete compacted by vibratory roller compaction (ACI 207.5R-99). The main difference between RCCP and Normal vibrated concrete (NVC) is the required consistency that directly affects the mix proportion requirements (Harrington et al., 2010). Fresh RCCP is stiffer than a typical concrete used in pavement construction (Khayat & Libre, 2014; Harrington et al., 2010). Therefore, due to difference in fresh properties of NVC and the RCCP, most of the techniques for mixture proportioning of NVC cannot be directly applied to the mix design of RCCP (Khayat & Libre, 2014).

Although, basic materials used to make RCCP are the same as those common to the production of NVC, but RCCP has a higher volume of aggregate, and lower binder and water contents, and hence, reduced paste volume (Mardani-Aghabaglou et al., 2013; Hazaree., 2011; Atiş, 2005; Hazaree et al., 2013). Aggregate content is typically 75 to 85% of the total volume of RCCP compared to 60 to 75% in NVC (Alexander & Mindess, 2010; Burwell et al., 2014). RCCP mixtures reportedly often require a higher proportion of fine to coarse aggregate compared to NVC, which can result in a more homogenous mixture and reduce the risk of segregation (Harrington et al., 2010; Khayat & Libre, 2014). Also, Aggregate used in RCCP differs from NVC in its gradation requirements (Khayat & Libre, 2014).

The use of chemical admixtures in NVC is common (Hazaree et al., 2013). However, Delatte (2014) has reported with the exception of retarders, admixtures are not often used for RCCP. The mechanical properties of NVC are highly influenced by cement hydration, however, the mechanical properties of RCCP are highly influenced by cement hydration and level of compaction (Kalantari et al., 2009). A study showed that a 3% decrease in compaction of RCCP reduces the compressive strength by nearly 30%, which in turn decreases the concrete's durability (Gauthier & Marchand, 2005). Distribution of paste in RCCP is less homogeneous than in NVC, however, the compressive strength of RCCP is comparable to that of NVC (Khayat & Libre, 2014; Harrington et al., 2010; Gauthier et al., 2005). The modulus of elasticity of RCCP is similar to or slightly higher than that of NVC when the mixes have similar cement contents (ACI 325.10R-95). Test results have indicated that mechanical properties such as compressive strength, modulus of elasticity, and fatigue strength of RCCP are similar to those of conventional paving concrete (Naik et al., 2001).

Table 2.1: Differences between NVC and RCCP (ACI 325.10R-95; Kett, 2000; Naik, et al., 2001; Gauthier & Marchand, 2005; Kalantari et al., 2009; Khayat & Libre, 2014; Sudarshan & Chandrashekar,2017; Aghaeipour & Madhkhan, 2019)

NVC for different applications including concrete pavement	RCCP
Slump about 25 to 75 mm	Zero slump concrete
Plastic and flowable mixture	Dry and stiff mixture
60 to 75 percent of the volume of concrete is occupied with well-graded aggregate	75 to 85 percent of the volume of concrete is occupied with well-graded aggregate
ASTM C33 Standard limit is offered for aggregate gradation	ACI325.10R and PCA standards are suggested for aggregate gradation
Lower fine aggregate	Larger-sized fine aggregate to ensure a uniform concrete mix with less surface voids
The mechanical properties is highly influenced by cement hydration	The mechanical properties are highly influenced by cement hydration and level of compaction
Water-to-cement ratio is about 0.40 to 0.45	Water-to-cement ratio is less than conventional concrete about 0.2 to 0.4
Drying shrinkage 700 µm/m or more	less drying shrinkage, generally between 400 and 500 µm/m
Consolidation occurs internally	Consolidation is accomplished externally by rollers
Cement content does not have restriction. Usually cement content is around 15% by volume and more. It depends on strength requirement.	Cement content restricted to a minimum, usually 12% by volume. Often, 12% cement content satisfies the strength requirement for RCCP.
The maximum size of aggregate depends on project requirement	Usually the maximum sizes of aggregate restricted to 19 mm to avoid segregation
Cracks are controlled by sawing joints	Joints are not always sawed in RCC
The use of Air Entraining is common	RCC is generally not air-entrained

2.3 Mixture proportioning methods for RCCP

Over the years, several methods with different approaches were used for RCCP mixture proportions. Almost, all methods require number of trial batches to achieve optimum mixture proportions. It should be noted, regardless of method, the RCCP mixture design should meet certain requirement. The RCCP mixture proportion should be adjusted properly to get specified mechanical properties with minimal costs, suitable for compaction, closed surface texture and ensure long term performance of RCCP (Marchand et al., 1997).

The most common mixture design methods for RCCP are classified into the following two major groups (Harrington et al., 2010; Khayat & Libre, 2014; Naik, et al., 2001). 1) To meet the special limits of consistency 2) to meet the maximum dry density.

2.3.1. Consistency approach

This approach concentrates on workability of RCCP in fresh state. In this method one of specific mixture parameters; cementitious materials content, water content, or aggregate content, vary to achieve specified consistency by modified Vebe test. From the test results, specified mixture parameters that meet the required strength are selected. It should be noted that the modified Vebe time is influenced by the water content, MNSA, fine aggregate content, and the amount of aggregate finer than the 75 μm (sieve No. 200) (Khayat & Libre, 2014).

2.3.2 Soil-compaction approach

Soil-compaction approach focuses on the relationship between dry unit weight and moisture content of the RCCP specimens. In this method the cementitious materials content usually vary between 12% and 14% of total mass of dry solids (Marchand et al., 1997). For fixed binder content mixtures, the different water contents are applied. In order to obtain the optimum moisture content of mixtures, accordance to ACI 211.3R.02, the dry density for mixtures with different moisture content is calculated. Then, the relationship between moisture contents and dry density is plotted for mixtures. Finally, from the moisture-density curve the optimum moisture content corresponding with the maximum dry density is determined. Such a typical relationship is shown in Figure 2.4.

An evaluation of RCCP in service indicates that slightly wetter mixes produce a better surface texture and help to improve compaction in the bottom half of the pavement lifts placed with tamping lay-down machines (Palmer, 1987). Usually, the wet density changes very little in the range of peak, even though the dry density is more significantly affected (ACI 207.5R89).

The basic concept in this method is to maximize the packing density of solid materials by adjusting the moisture content (Harrington et al., 2010; Khayat & Libre, 2014). In this method, grading of aggregate is very important to achieve a mixture with the highest packing and lowest void ratio. It is noticeable that soil-compaction approach is proposed for small to medium size projects (Choi & Groom, 2001). Also, this method is more appropriate when small-size aggregates are used along with a relatively high content of cementitious materials (Khayat & Libre, 2014).

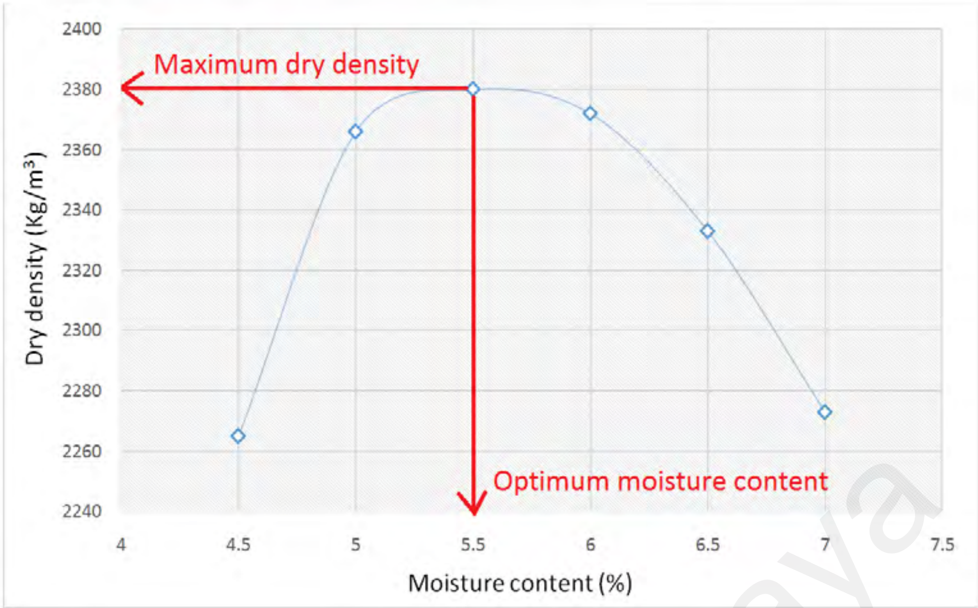


Figure 2.4: Typical moisture content-density relationship obtained in soil-compaction approach

2.3.3 Examples of RCCP mixture proportions

Among the most important characteristics of RCCP, its strength at early ages, its high speed, and its economic performance can be mentioned (Aghaeipour & Madhkhan, 2019). RCCP applications offer technical, economic and ecological solutions in many civil construction projects (Lopez-Uceda et al.,2018). The use of RCCP has increased steadily in the past few decades. It is an economical version of concrete pavement; whereas the construction cost of other types of pavement is constantly rising. In its mixture design, compactibility is an important factor for achieving high strength while workability is an essential factor for providing workable material. However, the satisfaction of both properties is difficult to achieve because of the effect of various factors such as aggregate gradation and water content. Appropriate combination of materials is significant for providing adequate compactibility and workability of this concrete (Chhorn et al., 2019). Table 2.2 lists some typical mixture proportions used on several projects in North America.

Table 2.2: Examples of RCCP mixture proportions (Harrington et al., 2010)

Reference/Construction site			Port of Tacoma, WA Intermodal Yard	CTL Mix	Chattanooga, TN	Brownsville, TX	South Carolina	Atlanta, GA I285 Shoulder	Canada PCA RD135
Binders	Cement	(pcy)	450	504	300	504	444	500	500[1]
	Fly ash	(pcy)	100	0	150	0	0	0	0
Aggregates	Maximum aggregate size (in.)	(in)	5/8	3/4	3/4	3/4	1	1/2	3/4
	Coarse aggregate	(pcy)	1,700	1,378	2,110	1,287	1,759	1,650	2,117
	Fine aggrgeate	(pcy)	1,700	2,106	1,657	1,762	1,658	1,650	1,349
	Fines (passing No. 200)	(%)	3-7	2	3.6	2	--	--	--
Water[2]		(pcy)	257	211	190	236	216	266	160
Admixtures	Water reducer or retarder	(oz)	--	--	18	--	--	0	41
	Air entraining admixture	(oz)	--	--	0	--	--	0	41
Compaction parameters	Maximum wet density	(pcf)	154.3	152	--	147.2	--	150.3	156.9
	w/cm	--	0.47	0.42	0.42	0.47	0.49	0.53	0.32
	Aggregate/cementitious (weight)	--	6.18	6.91	8.37	6.05	7.70	6.60	6.93
	Fine aggregate/total aggregate	(%)	50.00	60.45	43.98	57.79	48.52	50.00	38.9
Strength	Compressive, 3-day	(psi)	1,810	5,460	5,090[3]	3,046	3570	3866	--
	Compressive, 28-day	(psi)	6,050	7,900	6,100	4,946	5,220	5,157	8,368
	Flexural, 3-day	(psi)	525	690	611[3]	493	--	--	--
	Flexural, 28-day	(psi)	770	900	702	638	--	--	--
	Ratio 28-day flexural/compressive	(%)	11.39	11.39		12.90	--	--	--

Notes:
1. 7 percent silica fume blended portland cement
2. Water content is total water based on oven-dried weight of aggregates, except for Canada and Chattanooga mixes, where reported water is free water based on saturated surface dry condition of aggregates.
3. 7-day compressive and flexural strength

2.4 Workability of RCCP

Workability is often referred to as the ease with which a concrete can be transported, placed and consolidated without excessive bleeding or segregation or the internal work done required to overcome the frictional forces between concrete ingredients for full compaction (UMP, 2014). ACI 116R-2000 defines workability as "that property of freshly mixed concrete which determines the ease and homogeneity with which it can be mixed, placed, consolidated, and finished".

Workability is an important property for RCCP that governs the ease of placement and provides an indication of production consistency. A typical test method that is usually used for measure of needed work to compact RCCP, is the modified Vebe time test. The Vebe time test gives useful results for stiff concrete's workability which measures the work needed to compact the concrete (Chi & Huang, 2014). VeBe time, which is the time that cement mortar appears at the surface of the surcharge (Fakhri & Amoosoltani, 2017). Based on ACI 325.10R-95 VeBe time has been limited to 30-40 s for producing RCCP, while Gauthier and Marchand (2005) concluded that VeBe time must be between 40 and 90 seconds when RCCP is placed.

The effects of cement content and water-to-cement ratio on the workability of RCCP have been investigated by Tian and Liu (2013). Five different cement contents are used in RCCP mixtures. The water cement ratios of these mixtures are 0.5. As can be seen increasing cement content leads to decreasing Vebe time. In addition, with the increase of water to cement ratio, the values of Vebe time are decreased. The test results are shown in Figure 2.5 and Figure 2.6. Suitable aggregate grading and the correct selection of C/F ratio are key factors for obtaining a good RCCP mixture in terms of workability, compactability, minimizing voids, reducing segregation, as well as surface finish (Khayat & Libre, 2014). In addition, correct aggregate selection affects the water requirement and need for cementitious materials for an RCCP with acceptable mechanical properties.

A fine aggregate volume smaller than 75 μm (fine aggregate passing through sieve #200) in an RCCP mixture has a significant effect on this type of concrete, in both fresh and hardened states (Khayat & Libre, 2014; Harrington et al., 2010). However, RCCP mixtures reportedly often require a higher proportion of fine to coarse aggregate compared to conventional concrete, which can result in a more homogenous mixture and reduce the risk of segregation (Khayat & Libre, 2014; Harrington et al., 2010).

Aggregates strongly influence concrete's fresh and hardened properties and its mixture proportions (Yuqiang et al., 2011; Rao et al., 2016). Also, the most efficient way to achieve workable and high strength RCCP is by providing a well-graded aggregate (Khayat & Libre, 2014; Harrington et al., 2010).

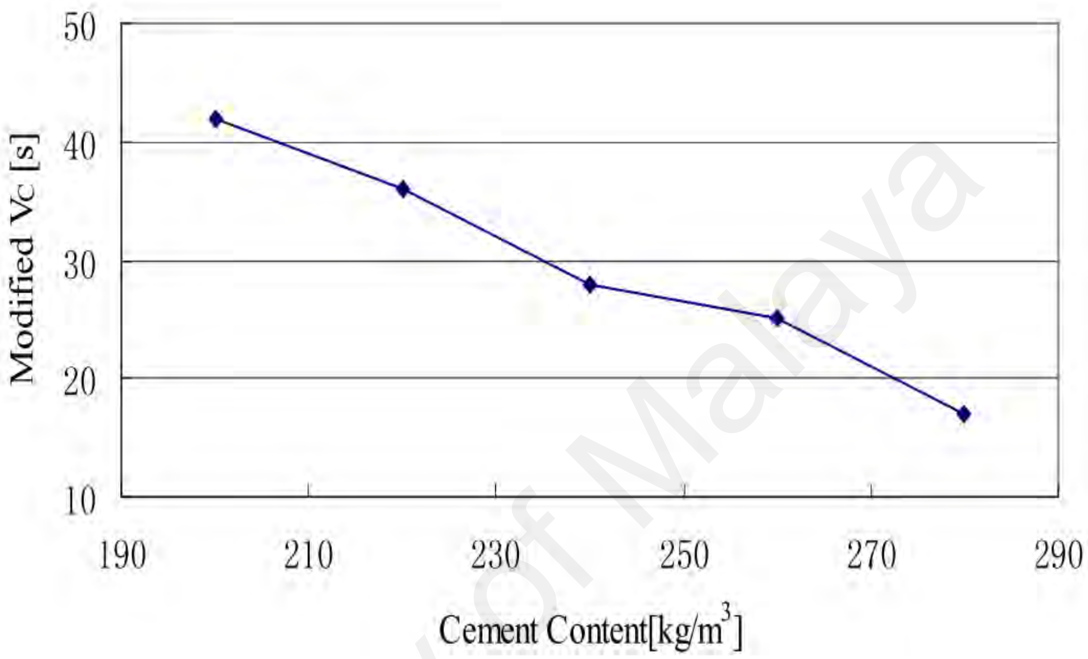


Figure 2.5: Effects of cement content on workability (Tian & Liu, 2013)

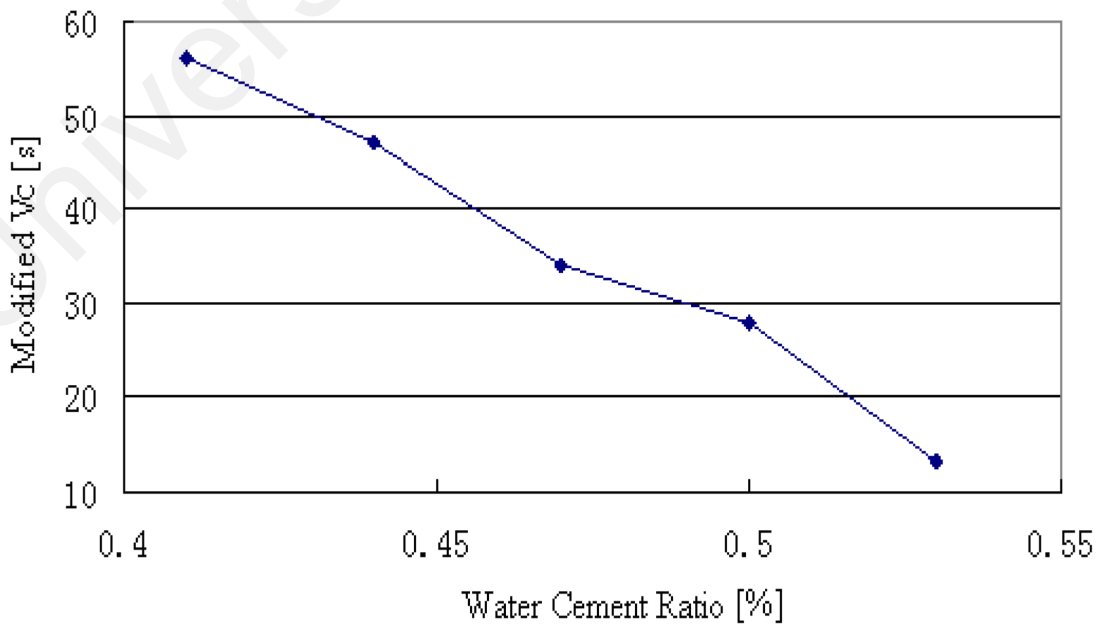


Figure 2.6: Effect of water-to-cement ratio on workability (Tian & Liu, 2013)

Also, in different study the workability of RCCP over the time is investigated. The results are shown in Figure 2.7.

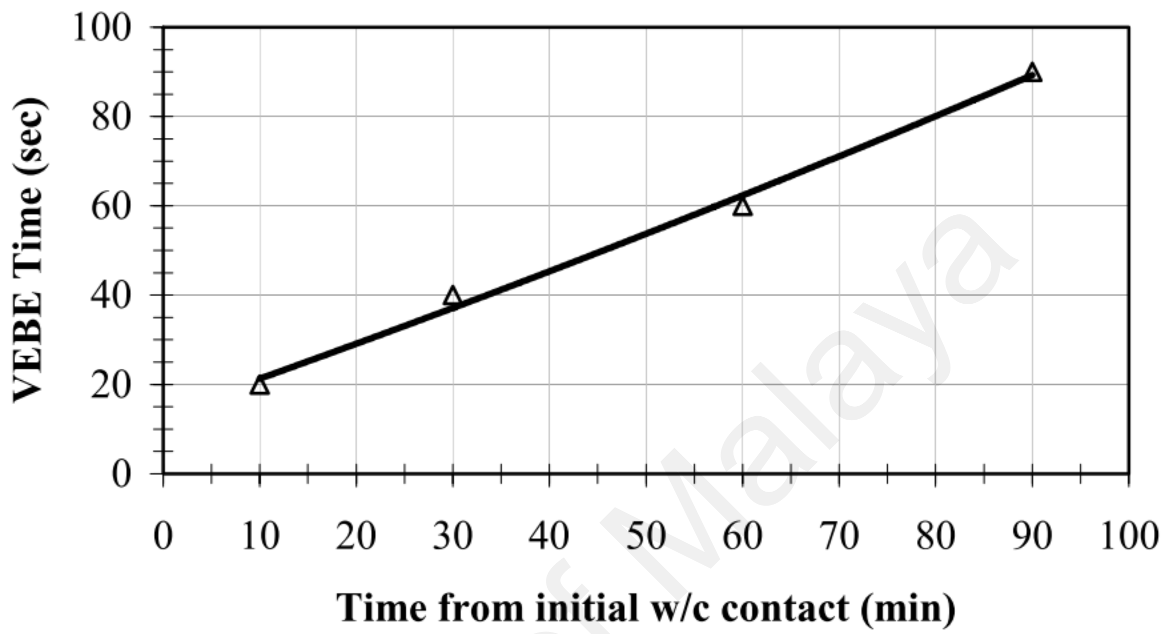


Figure 2.7: RCCP workability over time (Gauthier & Marchand, 2005)

2.5 Mechanical properties of RCCP

The hardened properties of RCCP depend on the proper selection of binder composition and its volume, water to binder ratio, and aggregate characteristics. For conventional concrete, the strength depends on the mixture proportions. However, for RCCP, strength depends on the level of compaction in addition to the mixture proportions (Delatte, 2014). A study showed that a 3% decrease in compaction of RCCP reduces the compressive strength by nearly 30%, which in turn decreases the concrete's durability (Gauthier & Marchand, 2005).

2.5.1 Compressive strength

The compressive strength is the most commonly used property to describe the quality of concrete in practice (Wiegrink et al., 1996). Based on ASTM C 330-89, the 28-day cylinder compressive strength should not be less than 17 MPa. The compressive strength of RCCP is comparable to that of conventional concrete, typically ranging from 28 to 41MPa (Harrington et al., 2010; Gauthier & Marchand, 2005; Khayat & Libre, 2014). The density of the RCCP ranged from 2340 to 2510 kg/m^3 that the corresponding compressive strength ranged from 20 to 55 MPa (Delatte, 2014).

RCCP with low water-to-cement ratio leads to low porosity cement matrix that also contributes to the high compressive strength of the concrete. However, very low water-to-cement ratio results in a dry mix that cannot be compacted properly. Improper compaction causes many compaction voids. A high number of compaction voids may form an interconnected network that seriously jeopardizes durability and decrease compressive strength (Khayat & Libre, 2014). The coarse to fine aggregate ratio is very important for RCCP compressive strength. The Figure 2.8 shows the role of coarse to fine aggregate ratio in different cement content.

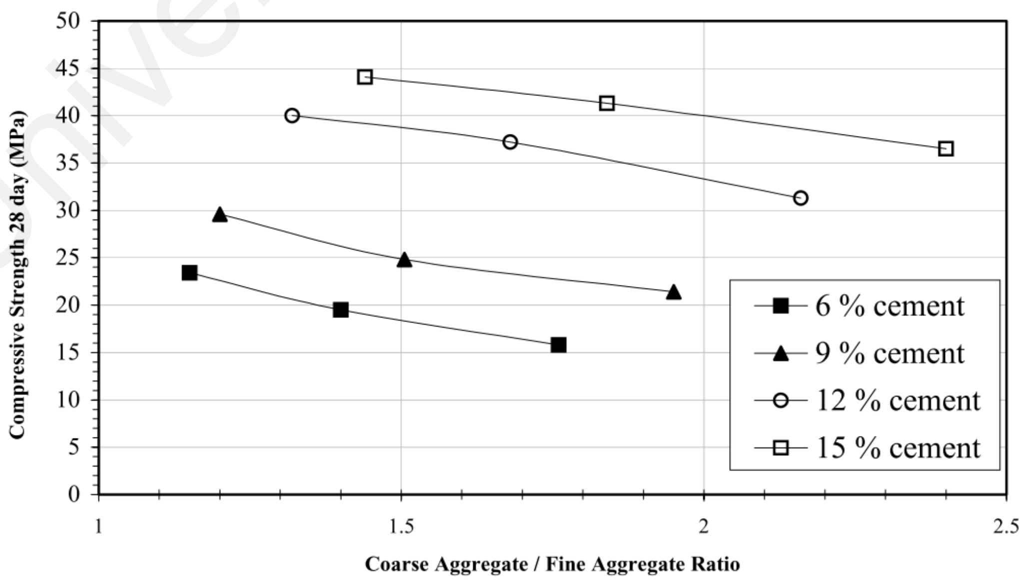


Figure.2.8: Influence of the coarse-fine aggregate ratio on 28-day compressive strength (Nanni, 1988)

RCCP mixes with a cementing material content of approximately 300 kg/m^3 and a water-cementing materials ratio of 0.35 can develop compressive strength of 40 MPa and flexural strength of 5.0 MPa after three days of curing (Gauthier & Marchand, 2005). Missouri Standard Specifications for Highway Construction (2004) requires that the RCCP mix design shall have a minimum compressive strength of 24 MPa at 28 days when specimens prepared according to ASTM C 1176 or ASTM C 1435.

Researches (Engineer & Rashed, 2000; Khayat & Libre, 2014) highlighted that nominal maximum size of coarse aggregate as well as fine aggregate passing through sieve #200 (75 μm) have important role in fresh and hardened properties of RCCP. For many applications such as soils, base and asphalt have demonstrated that the best performance is derived from blend of equidimensional particles that are well-graded from coarsest to finest (Delatte, 2014). The load carrying capacity of RCCP is dependent on the compaction process that creates friction between the confined particles or interlocking aggregates.

2.5.2 Splitting Tensile strength

The significant role of tensile strength in fracture mechanism of concrete has been reported (Li, 2004). It is common practice to neglect the tensile strength of concrete in design and assumed to be zero (Kaufmann, 2013). However, the tensile strength is of interests for some intentions such as design of highway, airfield slabs and resistance to cracking. Critical Applied flexural stress is the maximum tensile stress at the bottom of the concrete pavement slab (Harrington et al., 2010). Therefore, flexural test is generally used for determining the tensile strength of RCCP instead of the splitting tensile test.

It is reported that splitting tensile strength in RCCP is between 2 and 5.5 MPa and it is generally a little lower than flexural strength (Delatte, 2014). British Department of

Transport (1976) specify that concrete to be used in road construction shall have at least 1.85 MPa splitting tensile strength at 7 days.

2.5.3 Flexural tensile strength

Flexural tensile strength of RCCP mixture is one of the controversial aspects of these mixtures which not only affects design results but also directly affects the resistance of mixture against fatigue and thermal cracking (Fakhri & Amoosoltani, 2017). Project quality control and opening the pavement to traffic may be on the basis of compressive strength, even though the pavement is designed on the basis of flexural strength (Delatte, 2014).

The flexural strength of adequately designed RCCP mixes is generally higher than that of conventional concrete (Gauthier & Marchand, 2005). The ratio between flexural strength and compressive strength in RCCP is about 0.15, as compared with 0.10 to 0.12 in the case of conventional concrete (Khayat & Libre, 2014). However, it is reported that the relationship between the compressive and flexural strengths of RCCP is similar to that of conventional concrete (ACI 325.10R-95). Because of the difficulty of making beams and sawing beam specimens, there is limited information on flexural strengths (ACI, 1995). The flexural strength of RCCP, depending on the mix design, is generally high-ranging from 3.5 to 7 MPa. The British Airport Authority (BAA) (1977) limits the flexural tensile strength to 4 MPa at 28 days. Flexural strength is commonly estimated from compressive strength with the following equation given by ACI 318 and ACI 325.10:

$$f_r = c\,\sqrt{f_c} \qquad \text{(Eq.2.3)}$$

Where:

f_r is flexural strength of concrete

f_c is compressive strength of concrete

C is a constant factor

The constant factor is C=7.5 for conventionally vibrated concrete. Due to the density of the paste in RCCP and the strength of its bond to the aggregate particles, the constant value is usually higher than the conventional concrete (Khayat & Libre, 2014). The recommended value is between 9 and 11 depending on actual RCCP mix (ACI 325.10).

2.6 Modulus of elasticity

The modulus of elasticity expresses the ratio between the applied stress and strain in the linear region. It has reported that the modulus of elasticity of RCCP is similar to or slightly higher than that of conventional concrete when the mixes have similar cement contents (Khayat & Libre, 2014). Also, ACI 325.10 reported that RCCP modulus of elasticity may be similar to or slightly higher than that of conventional concrete with similar cement contents.

The average modulus of elasticity for RCCP is about 30 GPa at 28 days of curing (regardless of temperature), whereas the modulus of asphalt pavement is about 3.3 GPa at 20°C (Gauthier & Marchand, 2005). Ouellet (1998) showed in his experimental studies that the elastic modulus of the RCCP is influenced by the properties of the two phases present in this mixture, which are the hydrated cement paste and the aggregates.

2.7 Porosity

A method of calculating the total volume of capillary voids, popularly known as porosity (Mehta, 2006). Porosity and pore size distribution of RCCP depend on the water to cement and the degree to which the concrete is compacted (Khayat & Libre, 2014). The low water-to-cement ratio of RCCP mixtures produces a low-porosity cement matrix that also contributes to the high compressive strength of the concrete. It should be noted that Kuzu et al. (1990) have indicated that the porosity of RCC should not be more than 3%.

2.8 Admixtures

Chemical admixtures; water reducers, air entraining agents and retarders commonly are used in conventional concrete. However, Delatte (2014) has reported with the exception of retarders, admixtures are not often used for RCCP. Also, Khayat and Libre (2014) reported chemical admixtures have had only limited use in RCCP mixtures. Because RCCP mixtures are very dry, admixtures must be added in higher quantities than are used in conventional concrete to be effective (Gauthier & Marchand, 2005; Khayat & Libre, 2014). Chemical admixtures used in RCCP mixes should conform to ASTM C 494.

2.8.1 Water reducers

Water reducers or superplasticizers are rarely used in RCCP production (ACI 325.10R-95). Some producers have found that increase the cement content is cheaper than the use of water reducing admixtures (Harrington et al., 2010). However, this can lead to other issues, such as greater shrinkage of the mixture. It has reported that water reducers have been successfully used with RCCP to help distribute the cement paste uniformly throughout the mix and to improve workability during paving (Portland cement Association, 2006; Chun et al., 2008). However, the effect of water-reducing admixtures tends to decrease dramatically with the reduction of the water content (Chun et al., 2008). Figure 2.9 shows the absorbance of water reducing admixtures to the cement particles and through electrical repulsion lower the inter-particular attraction so that flocs of cement break up.

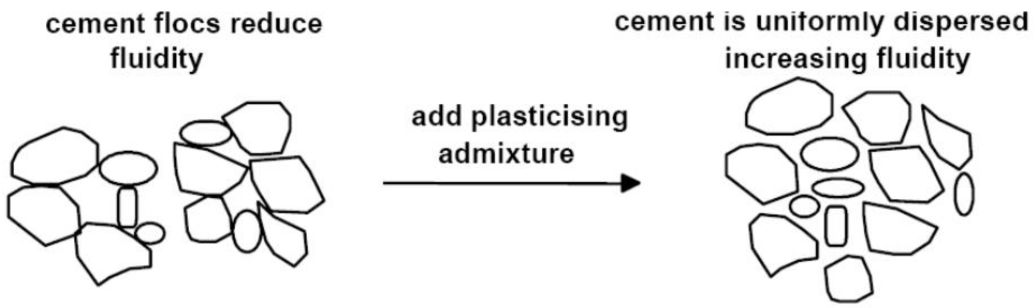


Figure 2.9: Schematic sketch of plasticizing mechanism (Dransfield, 2006)

Chemical admixtures; water reducers, air entraining agents and retarders commonly are used in conventional concrete. However, Delatte (2014) has reported with the exception of retarders, admixtures are not often used for RCCP. Also, Khayat and Libre (2014) reported chemical admixtures have had only limited use in RCCP mixtures. Because RCCP mixtures are very dry, admixtures must be added in higher quantities than are used in conventional concrete to be effective (Khayat & Libre, 2014; Gauthier & Marchand, 2005).

Nowadays, more than 70% of in-situ concrete in the world is produced by the ready mixed concrete industry. The ready mixed concrete producers are using a superplasticizier admixture which is readily available from various manufacturers (Alsadey, 2015). Because superplasticizers are one of the most important ingredients used in concrete, the research and development of superplasticizer have attracted great attention recently (Pei et al., 2000). A review on literature showed that limited data on the use of super plasticizer in RCCP has been reported which may not be sufficient to draw conclusion. In the most previous studies, the use of super plasticizer in RCCP is not recommended due to lower water content used in RCCP production.

2.8.2 Air Entraining Agents (AEA)

Air entrainment achieved through the stabilizing action of air entraining admixture results in the formation of discrete, spherical, uniformly distributed air-voids or bubbles (ranging between 10 to 1000 μm) dispersed throughout the mixture (Hazaree et al., 2013). Entraining a consistent amount of air in RCCP is quite difficult, particularly with mixtures having no measurable slump (Marchand et al., 1997; ACI 325.10R-95; ACI 309.5R-00). Air entraining admixtures have not been used extensively in RCCP because acceptable freeze-thaw durability can be achieved without air entrainment (Harrington et al., 2010). However, proper air-entrainment of RCCP is the best way to assure adequate frost resistance (PCA, 2004).

A laboratory study on the mechanical behavior and freeze-thaw resistance of low-cement RCCP revealed that the addition of an air-entraining admixture produced a network of spherical micro bubbles that were well distributed throughout the matrix (Ouellet et al., 1998). However, a survey of existing RCCP carried out by the U.S. Army Corps of Engineers has indicated that the use of an air- entraining agent was not very efficient, even at large dosages (Ragan, 1986).

Andersson (Anderson, 1987) states that attempts to entrain air in RCCP mixtures can be successful if the air-entraining agent is premixed with the cement paste, a small portion of the coarse aggregate, and a superplasticizer before adding sand. Similar results were obtained, in the laboratory, by Gomez-Dominguez (1987). He reported that a significant number of spherical air bubbles can be entrained in RCCP mixtures when the paste fraction is premixed with the admixture in a counter-current pan mixer. Also, in other study was found that attempts to entrain air in RCCP mixtures can be successful if the air entraining agent is premixed with the cementitious paste (a mixture of cementitious materials and water), a small portion of the coarse aggregate, and a super plasticizer before adding the sand (Chun et al., 2008). Experimental investigation indicated that very dry mixtures require air entraining agents 5 to 10 times greater than conventional concrete (Khayat & Libre, 2014). Further research is still required in producing air-entrained RCCP with properly distributed air bubbles. Figure 2.10 shows the basic chemical nature of surfactant based air entraining agents and the distribution of surfactant molecules at the water-air interface.

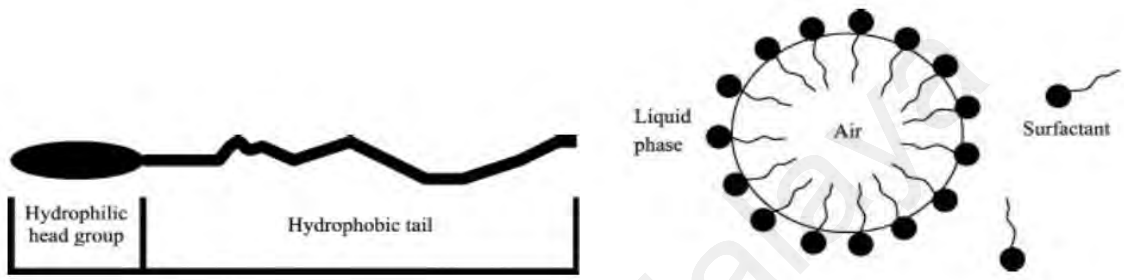


Figure 2.10: The basic chemical nature and the distribution of air entraining agents surfactant molecules at the water-air interface (Du & Folliard, 2005).

2.8.3 Retarding admixture or retarder

These admixtures retard or slow the rate of cement hydration, preventing mixtures from setting before it is laid and compacted. It does not plasticize significantly and have little or no effect on the water demand or other properties of the concrete (Dransfield, 2006). Usually it is observed that the long term strength is greater than the strength of non-delayed concrete (Aïtcin, 2008).

Harrington et al. (2010) reported that retarding admixtures may delay the onset of or slow down RCCP hydration and can thus help increase the time for compaction and improve the bond between adjacent lanes or successive layers. Also, Marchand et al. (1998) was found that the addition of a set-retarding admixture can also be effective to allow a delay of the rolling process without the formation of cold joints. In addition, it could help in allowing a slightly longer "working time," particularly in terms of dealing with longitudinal construction joints (Mueller, 1990).

2.9 Bond strength between lifts

This test is used for determination of the relative bond strength between successive layers of RCCP in multiple-lift forms of construction. Khayat and Libre (2014) has determined that the relative bond strength between two lifts of tested RCCP is about half of the corresponding strength determined within a single lift. In addition, it has reported that 60 to 90 percent of the parent concrete tensile strength can be achieved if the time between placement and compaction of the lifts is limited to 30 to 50 minutes (ACI 309.5R-00).

2.10 Light weight aggregate in RCCP

Lightweight aggregate concrete (LWAC) has been successfully used for a number of applications for decades and is also known for its high strength to weight ratio, better heat insulation, sound absorption, frost resistance, low coefficient of thermal expansion, good tensile strength and high-durability (Mouli & Khelafi, 2008; Shafigh et al.,2010; Maghsoudi et al., 2011). ACI 213R-87 defines structural lightweight aggregate concretes as a concrete having a minimum 28-day compressive strength of 17 MPa and air-dry density of below 1850 kg/m³.

Lightweight aggregates have been used in concrete pavement. The use of lightweight aggregate, which was a locally manufactured expanded clay was considered in Texas for an experimental section of highway. The concrete pavements built with lightweight aggregate showed relatively less surface distress than normal weight aggregate sections after 24-year. After 34 years the normal concrete had developed additional cracks besides the preformed ones. Spalls were also observed in this concrete section. The lightweight aggregate concrete pavement was in relatively better condition (Sarkar,1999). In other study Ledbetter et al. showed that the use of lightweight aggregate for concrete pavement design is applicable, and that final performance from the effects of warping stresses and pavements deflection could be better than that of pavements made with normal concrete (Ledbetter et al.,1966).

The use of lightweight aggregate in concrete pavement has many advantages: (1) less cracking risk for the same strain (2) equal to or better freeze-thaw durability (3) reduced risk of alkali-aggregate reactions (Delatte, 2006). In addition, in some applications such as bridge, the use of lightweight aggregate in pavement result in: (1) reduced dead load and increased allowable live loads (2) continued use of bridge without decreasing its load capacity (3) increased number of lanes with the same columns and girders (4) decreased construction costs and time (Duan & Chen,1999).

2.11 Structural design of RCCP

RCCP are constructed as plain, undoweled, and unreinforced pavements. The structural behavior of RCCP is similar to that of equivalent normal concrete pavements. Thickness design for RCCP employs the same basic strategy as for conventional concrete pavements: keeping the pavement's flexural stress and fatigue damage caused by wheel loads within allowable limits.

In the structural design of concrete pavements, pavement thickness is a function of expected loads, concrete strength (modulus of rupture), and soil characteristics. The minimum thickness of an RCCP is typically 10 cm, with a single-lift maximum thickness of 25.4 cm.

Thickness design procedures for RCCP for heavy industrial applications (such as ports and multimodal terminals) have been developed by the PCA. The design approach involves the assumption that the pavement structure can withstand loads of certain magnitudes at certain repetition levels without failing. Because the critical stresses in RCCP are flexural, fatigue due to flexural stress is used for thickness design. The stress ratio, as used in fatigue relationships, is the ratio of flexural stress to flexural strength:

$$Stress\ Ratio = \frac{Critical\ Applied\ Flexural\ Stress}{Flexural\ Strength} \quad \text{(Eq.2.4)}$$

where: Critical Applied Flexural Stress is the maximum tensile stress at the bottom of the concrete pavement slab, and Flexural Strength (or modulus of rupture) is the flexural strength of concrete as determined by beam testing using third-point loading at (ASTM C78; AASHTO T97or CSAA23.2-8C).

In RCCP thickness design, the pavement thickness is increased or the strength of the concrete is increased until the stress ratio is reduced sufficiently to provide for adequate fatigue performance.

Flexural fatigue research on RCCP has shown that its fatigue behavior is very similar to that of conventional concrete. Figure 2.11 shows the results of fatigue tests on beams obtained from full-scale pavement test sections for four different RCCP mixtures. In the figure, the line marked 50 percent is the best fit of the research data points, and the 95 percent line includes 95 percent of the data points. Below these lines, the RCCP design curve is set to provide a degree of conservatism similar to that used for conventional concrete in PCA's design procedures for highways and airports (PCA 1987).

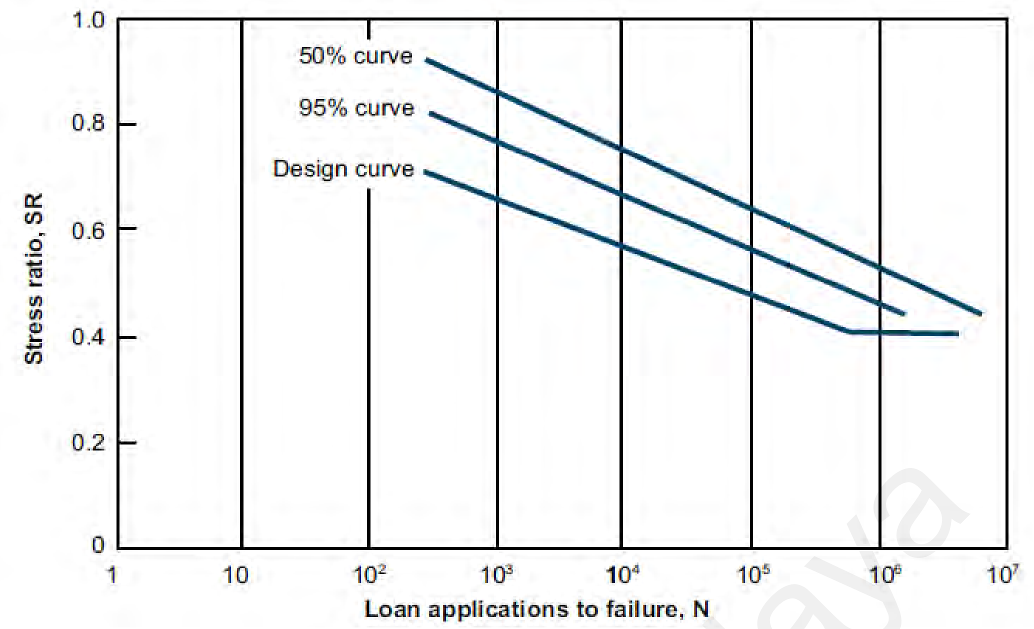


Figure 2.11: Fatigue relationship for RCCP

The principal RCCP properties affecting thickness design are flexural strength and fatigue behavior. In the design process, a pavement thickness is selected to keep flexural stresses and fatigue effects caused by wheel loads within safe limits. Stresses and fatigue caused by wheel load placement are greater for loads placed at pavement edges and joints than for loads placed at the pavement interior (PCA 1987). Therefore, joint performance (percent load transfer efficiency) plays a significant role in the fatigue life of concrete pavements.

To reduce stresses from edge loading, the pavement can be widened one foot or more, in which case the pavement is considered to have supported edges. In RCCP commercial and industrial parking areas, there is relatively little area adjacent to free edges, and vehicle loads are applied mostly to interior slabs. Therefore, pavements can be designed assuming supported edges (ACI 330R-08).

The following information is needed to carry out a thickness design for an RCCP (PCA 1987):

1. Supporting strength of the subgrade or subbase-subgrade combination (k-value)

2. Vehicle characteristics:

• Wheel loads at operating conditions

• Wheel spacing

• Tire characteristics (contact area, contact pressure)

• Number of load repetitions during the design life of the pavement

3. Flexural strength of RCCP

4. Elastic modulus of RCCP

The vehicle loading is expressed as an equivalent number of repetitions of an 18 kip (8.2 metric tons) single-axle loading, and, as a further simplification, the range of equivalent repetitions of the basic loading (i.e., traffic) is designated by a numerical scale defined as the pavement design index (Table 2.3).

Table 2.3: Pavement design index values

Traffic Category	Pavement design index for road or street classification					
	A	B	C	D	E	F
I	2	2	2	1	1	1
II	3	2	2	2	2	1
III	4	4	4	3	3	2
IV	5	5	5	4	4	3
IV A	6	6	6	5	5	4
V (60 kip track-laying vehicles or 15-kip forklifts)	7	7	7	7	7	(*)
500/day	6	6	6	6	6	(*)
200/day	6	6	6	6	6	(*)
100/day	6	6	6	6	6	6
40/day	6	6	6	5	5	5
10/day	5	5	5	5	5	5
4/day	5	5	5	5	4	4
1/day	5	5	5	4	4	4
VI (90 kip track-laying vehicles or 25-kip forklifts)						
200/day	9	9	9	9	9	(*)
100/day	8	8	8	8	8	8
40/day	7	7	7	7	7	7
10/day	6	6	6	6	6	6
4/day	6	6	6	6	6	6
1/day	5	5	5	5	5	5
1/week	5	5	5	4	4	4
VII (120 kip track-laying vehicles)						
100/day	10	10	10	10	10	10
40/day	9	9	9	9	9	9
10/day	8	8	8	8	8	8
4/day	7	7	7	7	7	7
1/day	6	6	6	6	6	6
1/week	5	5	5	5	5	5

*Traffic limited to 100 vehicles per day

2.11.1 ACI Design Procedures

Manual design methods (tables) can be used to determine RCCP thickness for streets, local roads, and parking lots that carry mixed-vehicle traffic.

2.11.1.1 Parking Lots

Table 2.4, replicated from Design and Construction of Concrete Parking Lots (ACI 330R-08), can be used to determine RCCP thickness. This table is based on a 20-year design with no dowels.

Table 2.4: Design of concrete parking lots (ACI 330R-08)

Twenty-year design thickness recommendations, in. (no dowels)													
		k = 500 psi/in. (CBR = 50; R = 86)				k = 400 psi/in. (CBR = 38; R = 80)				k = 300 psi/in. (CBR =26; R = 67)			
	MOR, psi:	650	600	550	500	650	600	550	500	650	600	550	500
Traffic category*	A (ADTT =1)	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.5
	A (ADTT = 10)	4.0	4.0	4.0	4.5	4.0	4.0	4.5	4.5	4.0	4.5	4.5	4.5
	B (ADTT = 25)	4.0	4.5	4.5	5.0	4.5	4.5	5.0	5.5	4.5	4.5	5.0	5.5
	B (ADTT = 300)	5.0	5.0	5.5	5.5	5.0	5.0	5.5	5.5	5.0	5.5	5.5	6.0
	C (ADTT = 100)	5.0	5.0	5.5	5.5	5.0	5.5	5.5	6.0	5.5	5.5	6.0	6.0
	C (ADTT = 300)	5.0	5.5	5.5	6.0	5.5	5.5	6.0	6.0	5.5	6.0	6.0	6.5
	C (ADTT = 700)	5.5	5.5	6.0	6.0	5.5	5.5	6.0	6.5	5.5	6.0	6.5	6.5
	D (ADTT = 700)†	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5
		k = 200 psi/in. (CBR = 10; R = 48)				k = 100 psi/in. (CBR = 3; R = 18)				k = 50 psi/in. (CBR = 2; R = 5)			
	MOR, psi:	650	600	550	500	650	600	550	500	650	600	550	500
Traffic category*	A (ADTT =1)	4.0	4.0	4.0	4.5	4.0	4.5	4.5	5.0	4.5	5.0	5.0	5.5
	A (ADTT = 10)	4.5	4.5	5.0	5.0	4.5	5.0	5.0	5.5	5.0	5.5	5.5	6.0
	B (ADTT = 25)	5.0	5.0	5.5	6.0	5.5	5.5	6.0	6.0	6.0	6.0	6.5	7.0
	B (ADTT = 300)	5.5	5.5	6.0	6.5	6.0	6.0	6.5	7.0	6.5	7.0	7.0	7.5
	C (ADTT = 100)	5.5	6.0	6.0	6.5	6.0	6.5	6.5	7.0	6.5	7.0	7.5	7.5
	C (ADTT = 300)	6.0	6.0	6.5	6.5	6.5	6.5	7.0	7.5	7.0	7.5	7.5	8.0
	C (ADTT = 700)	6.0	6.5	6.5	7.0	6.5	7.0	7.0	7.5	7.0	7.5	8.0	8.5
	D (ADTT = 700)†	7.0	7.0	7.0	7.0	8.0	8.0	8.0	8.0	9.0	9.0	9.0	9.0

*ADTT = average daily truck traffic. Trucks are defined as vehicles with at least six wheels; excludes panel trucks, pickup trucks, and other four-wheel vehicles.
k = modulus of subgrade reaction; CBR = California bearing ratio; R = resistance value; and MOR = modulus of rupture.
Note: 1 in. = 25.4 mm; 1 psi = 0.0069 MPa; and 1 psi/in. = 0.27 MPa/m

1. Car parking areas and access lanes_Category A
2. Shopping center entrance and service lanes_Category B
3. Bus parking areas, city and school buses
   Parking area and interior lanes _Category B
   Entrance and exterior lanes_Category C
4. Truck parking areas_Category B, C, or D

Truck type	Parking areas and interior lanes	Entrances and exterior lanes
Single units (bobtailed trucks)	Category B	Category C
Multiple units (tractor trailor units with one or more trailors)	Category C	Category D

*Select A, B, C, or D for use with Table 5-5.

Type of soil	Support	k, psi/in
Fine-grained soils in which silt and clay-size particles are predominate	Low	75 to 120
Sands and sand-gravel mixtures with moderate amounts of silt and clay	Medium	130 to 170
Sand and sand-gravel mixtures relatively free of plastic fines	High	180 to 220

2.11.1.2 Streets and Local Roads

Tables 2.5 and 2.6, replicated from the Guide for Design of Jointed Concrete Pavement for Streets and Local Roads (ACI 325.12R-02. These tables are based on a 30-year design.

Because RCCP does not have dowels or tie bars, Table 2.5 (integral or tied curb and gutter or shoulders (supported edges) is only used for RCCP when the shoulder is also RCCP and the joint between the lane and shoulder is considered a fresh joint and not a cold joint. Given the subgrade k, concrete flexural strength (modulus of rupture [MOR]), traffic classification, and annual average daily truck traffic (ADTT), the pavement thickness may be read directly from the table.

Table 2.5: Pavement thickness, in., with integral or tied curb and gutter or shoulders (supported edges) (based on ACI 325.12R)

k = 50 psi/in.					*k* = 100 psi/in.					Traffic classification	
MOR psi					MOR psi						
490	550	600	650	700	490	550	600	650	700		
6	6	6	5	5	6	5	5	5	5	ADTT = 3	Light residential
7	7	6	6	6	7	6	6	5	5	ADTT = 10	Residential
7	7	6	6	6	7	6	6	5	5	ADTT = 20	
7	7	6	6	6	7	6	6	6	5	ADTT = 50	
8	8	7	7	7	8	7	7	6	6	ADTT = 50	Collector
9	8	8	7	7	8	7	7	7	6	ADTT = 100	
9	8	8	8	8	8	8	7	7	7	ADTT = 500	
9	8	8	8	8	8	8	7	7	7	ADTT = 100	Minor arterial
9	9	8	8	8	9	8	7	7	7	ADTT = 500	
10	9	9	8	8	9	9	8	8	7	ADTT = 400	Major arterial
10	10	9	9	9	9	9	8	8	8	ADTT = 800	
11	10	10	10	10	10	9	9	9	9	ADTT = 1,500	
9	8	8	7	7	8	8	7	7	6	ADTT = 300	Business
9	9	8	8	8	8	8	7	7	7	ADTT = 700	
10	9	9	8	8	9	9	8	8	7	ADTT = 400	Industrial
10	10	9	9	9	9	9	8	8	8	ADTT = 800	

k = 200 psi/in.					*k* = 300 psi/in.					Traffic classification	
MOR psi					MOR psi						
490	550	600	650	700	490	550	600	650	700		
5	5	5	4	4	5	5	4	4	4	ADTT = 3	Light residential
6	5	5	5	5	6	5	5	5	4	ADTT = 10	Residential
6	6	5	5	5	6	5	5	5	4	ADTT = 20	
6	6	5	5	5	6	5	5	5	5	ADTT = 50	
7	7	6	6	6	7	6	6	6	5	ADTT = 50	Collector
7	7	6	6	6	7	6	6	6	5	ADTT = 100	
8	7	7	6	6	7	7	6	6	6	ADTT = 500	
8	7	7	6	6	7	7	6	6	6	ADTT = 100	Minor arterial
8	7	7	7	7	7	7	7	7	7	ADTT = 500	
8	8	7	7	7	8	7	7	7	7	ADTT = 400	Major arterial
9	8	8	7	7	8	8	7	7	7	ADTT = 800	
9	8	8	8	8	8	8	8	8	8	ADTT = 1,500	
7	7	7	6	6	7	7	6	6	6	ADTT = 300	Business
8	7	7	7	7	7	7	6	6	6	ADTT = 700	
8	8	7	7	7	8	7	7	7	7	ADTT = 400	Industrial
9	8	8	7	7	8	8	7	7	7	ADTT = 800	

Note: 1 in. = 25.4 mm; 1 psi/in. = 0.27 MPa/m.

Table 2.6: Pavement thickness, in., without curb and gutters or shoulders (unsupported edges) (based on ACI 325.12R)

k = 50 psi/in.					*k* = 100 psi/in.					Traffic classification	
MOR psi					MOR psi						
490	550	600	650	700	490	550	600	650	700		
7	7	6	6	6	7	6	6	6	5	ADTT = 3	Light residential
8	8	7	7	6	7	7	7	6	6	ADTT = 10	Residential
8	8	8	7	7	8	7	7	6	6	ADTT = 20	
8	8	8	7	7	8	7	7	7	6	ADTT = 50	
10	9	9	8	8	9	8	8	7	7	ADTT = 50	Collector
10	9	9	8	8	9	8	8	8	7	ADTT = 100	
11	10	9	9	8	10	9	8	8	8	ADTT = 500	
11	10	9	9	8	10	9	8	8	8	ADTT = 100	Minor arterial
11	10	10	9	9	10	9	9	8	8	ADTT = 500	
12	11	10	10	9	11	10	9	9	8	ADTT = 400	Major arterial
12	11	11	10	10	11	10	10	9	9	ADTT = 800	
12	12	11	11	11	11	10	10	10	10	ADTT = 1,500	
10	10	9	9	8	9	9	8	8	7	ADTT = 300	Business
11	10	9	9	9	10	9	9	8	8	ADTT = 700	
12	11	10	10	9	11	10	9	9	8	ADTT = 400	Industrial
12	12	11	10	10	11	10	10	9	9	ADTT = 800	
k = 200 psi/in.					*k* =300 psi/in.					Traffic classification	
MOR psi					MOR psi						
490	550	600	650	700	490	550	600	650	700		
6	6	5	5	5	6	5	5	5	5	ADTT = 3	Light residential
7	6	6	6	5	6	6	6	5	5	ADTT = 10	Residential
7	7	6	6	6	7	6	6	6	5	ADTT = 20	
7	7	6	6	6	7	6	6	6	5	ADTT = 50	
8	8	7	7	6	8	7	7	6	6	ADTT = 50	Collector
8	8	7	7	7	8	7	7	6	6	ADTT = 100	
9	8	8	7	7	8	8	7	7	7	ADTT = 500	
9	8	8	7	7	8	8	7	7	7	ADTT = 100	Minor arterial
9	8	8	8	8	9	8	8	7	7	ADTT = 500	
10	9	9	8	8	9	9	8	8	7	ADTT = 400	Major arterial
10	9	9	8	8	9	9	8	8	8	ADTT = 800	
10	9	9	9	9	10	9	9	9	9	ADTT = 1,500	
9	8	8	7	7	8	8	7	7	7	ADTT = 300	Business
9	8	8	7	7	8	8	7	7	7	ADTT = 700	
10	9	9	8	8	9	9	8	8	7	ADTT = 400	Industrial
10	9	9	8	8	9	9	8	8	8	ADTT = 800	

Street classification	Vehicles per day or average daily traffic, two-way	Heavy commercial vehicles (two-axle, six-tire, and heavier)	
		%	No. per day
Light residential	200	1 to 2	2 to 4
Residential	200 to 1,000	1 to 2	2 to 4
Collector	1,000 to 8,000	3 to 5	50 to 500
Minor arterial	4,000 to 15,000	10	300 to 600
Major arterial	4,000 to 30,000	15 to 20	700 to 1,500
Business	11,000 to 17,000	4 to 7	400 to 700
Industrial	2,000 to 4,000	15 to 20	300 to 800

2.12 The use of waste and by-product materials in RCCP

Concrete pavements is a suitable choice for highways, airports, streets, roads, parking lots and other types of infrastructure. Concrete pavements can provide many decades of service when design properly and built out of durable materials. A greater focus on long-term affordability, quality and efficiency is required for sustainable construction (Nagalakshmi, 2013). Sustainable concrete needs to have very low demand of inherent energy, produced with minimum waste, made of the most common resources in environment, have long lasting structure, have a high thermal mass as possible and be made of recycled and reusable materials (Naik, 2008).

One of the main producers of carbon dioxid is cement industry; for the fabrication of every ton of cement, 900 kg of CO_2 are emitted, accounting for 88% of the emissions associated with the average concrete mix (Babor et al., 2009).

It is very vital to identify a substitution for cement or non-renewable material such as granite to make a more cost effective and environmental friendly concrete, because annual production of more than 10 billion tons of concrete has made it the most essential construction material (Shafigh et al., 2014). The production of waste materials is an unavoidable in industries and human activities. These wastes are now most pressing environmental and economic issues of today's world. Concrete is an ideal material for recycling waste or industrial by-products (Delatte, 2014). Many waste materials that would end up in landfills can be used in concrete production. Ground-granulated blast-furnace slag (GGBFS), Rice husk ash (RHA) and Fly ash (FA), and are among materials that can be included in the recipe for concrete and further enhance its appeal. Using waste material such as FA, GGBFS and RHA as cementitious materials can potentially lead concrete industry into more green and sustainable industry which is able to reduce the pollution of gases emissions. From various kinds of concrete pavement, high potential capacity of RCCP for using waste materials in its mix proportion is reported by researchers (De Brito & Saikia, 2012). RCCP is an environmentally friendly pavement material due to it incorporates by-products from industries. RCCP is an attractive alternative to conventional road construction due to it is relatively easier to produce and more economical.

2.12.1 Waste and by-product materials as cement replacement

2.12.1.1 Fly ash

Different type of cementitious materials such as FA are used in concrete mixture due to they improve some engineering properties and may reduce the cost of production (Bentz & Ferraris, 2010). FA is composed of the fine particles of coal combustion product. FA contains much unfixed Silicon dioxide (SiO_2) and Aluminium oxide (Al_2O_3), therefore it possesses comparatively high potential activity. Morphologic, pozzolanic, and micro aggregate effects are the main significant effects of FA in concrete (Cao et al., 2000). The pozzolanic effect, as the main effect of FA, states the unfixed Al_2O_3 and SiO_2 in this pozzolanic materials that can be activated by calcium hydroxide ($Ca(OH)_2$) product from cement hydration and therefore produce more hydrated gel (Cao et al., 2000). The specific gravity of FA is usually in the range of 1.3 - 4.8, mainly consists of particle sizes less than 45 micrometre and generally spherical in shape (Joshi & Lohita, 1997).

According to ASTM C-618 there are two types of FA. They are classified in two classes of C and F, produced by burning brown coal and black coal, respectively. Compare to class C, class F FA, has generally low lime (less than 15%), with greater combination of SiO_2, Al_2O_3, Fe_2O_3 (more than 70%). While, class C of FA has higher lime content (usually more than 15%, often about 30%) (Gamage et al., 2013). Table 2.7 shows some standard specifications for the physical and chemical properties of two types of FA.

Table 2.7: Standards limits for the physical properties and chemical compositions of FA (ASTM C-618, 1992; BS 38, 1992; EN 450, 1994)

Properties	ASTM (1992) Class F	ASTM (1992) Class C	BSI	EN (1994)
Max moisture	3	3	0.5	-
Max loss on ignition (LOI)	12	6	7	5
Max sulfur trioxide (SO_3)	5	5	2.5	3
Max magnesium oxide (MgO)	5	5	4	-
Max Alkali	1.5	1.5	-	-
Min silicon dioxide (SiO_2)	-	40	-	-
Min SAF (SiO2+Al2O3+ Fe2O3)	70	50	-	-
Max free lime (CaO)	-	-	-	1 - 2.5
Pozzolanic activity index (PAI) min %	75	75	-	75% at 28 days. 85 % at 90 days
Max fineness (% of remaining on 45 µm sieve)	34	34	12.5	40
Max expansion	-	-	-	10mm

The production of FA has increased up to 900 million tonnes per year by 2008 and it is predicted to increase up to around 2000 million tonnes in year 2020 (Gamage et al., 2013; Malhotra, 2008). Millions of tonnes of FA are produced worldwide every year, producing 80 million tonnes per year of the total production in India, however, only less than 10% is used. It is reported that the majority of the FA is finding its way to landfill (Yerramala & Babu, 2011; Siddique, 2003).

Most of the RCCPs mixtures used by the U.S. Army Corps of Engineers contained either Class C or F FA (Ragan, 1988). It was found that FA can be used in high volumes (e.g., 50 -80% by mass of the binder) in RCCP (Yerramala & Babu, 2011). The use of RCCP containing high volumes FA could be a prudent option for the infrastructure development. In general, the use of FA in RCCP reduce the cost, make it easier to compact and decrease the heat of cement hydration (Chun et al., 2008). The chemical and physical properties of the FAs which have been used in RCCP mixtures are given in Table 2.8.

Table 2.8: The chemical and physical properties of the fly ashes used in RCCP. (Sun et al., 1998; Cao et al., 2000; Atiş et al., 2004; Atiş, 2005; Yerramala & Babu, 2011)

No	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O	Na_2O	LOI	Specific gravity	Reference
1	58.3	31.7	5.9	2	0.1	0.2	0.8	0.8	0.3	2.06	Amarnath and Ganesh Babu.
2	50.20	28.60	13.20	2.60	1.30	0.60	2.40	1	2.80	2.40	Atis.
3	44.90	25.20	7.50	2.40	1.20	0.28	2.90	1	15.60	2.28	Atis.
4	54.7	24.04	6.9	8.7	1.13	1.50	-	-	4.98	2.20	Cao et al.
5	51.83	32.13	5.96	3.74	1.05	0.18	-	-	1.31	-	Sun et al.
6	18.95	7.53	3.82	51.92	1.58	12.06	-	-	2.94	2.70	Atis et al.

a. The effect of non-standard and standard class F fly ash on properties of RCCP

Atis (2005) has studied properties of RCCP containing high volume FA which were collected from two different sources. The FA collected from the Drax power station could be classified as standard type F based on ASTM-C618. However, the FA collected from the Aberthaw power station could be considered as non-standard FA due to the remains of the Aberthaw FA on the 45-µm sieve and the loss on ignition value that were 22.50% and 15.60%, respectively. Both of these FAs were used as 50% and 70% cement replacement in a control mix containing 400 kg/m^3 ordinary Portland cement. The compressive and Flexural tensile strengths of RCCPs containing 50% (RCCP1) Drax FA were comparable or higher than the strength of the control mix at all ages. However, those values were lower than control mix for specimens containing 70% (RCCP2) Drax FA at all ages. The compressive strengths of concrete containing 50% (RCCP3) and 70% (RCCP4) Aberthaw FA was lower than the strength of its counterpart equivalent concretes made with Drax FA. The compressive strengths of RCCP3 were lower than the strength of control mixtures, however, it developed satisfactory at 28 days and high strength at one year. It is considerable that Aberthaw FA could be used in the concrete up to 50% as cement replacement. The mechanical properties of RCCPs containing 50% FA (Drax FA and Aberthaw FA) were higher than RCCPs containing 70% FA at all ages. Figures 2.12 and 2.13 indicate the mechanical strengths of RCCPs.

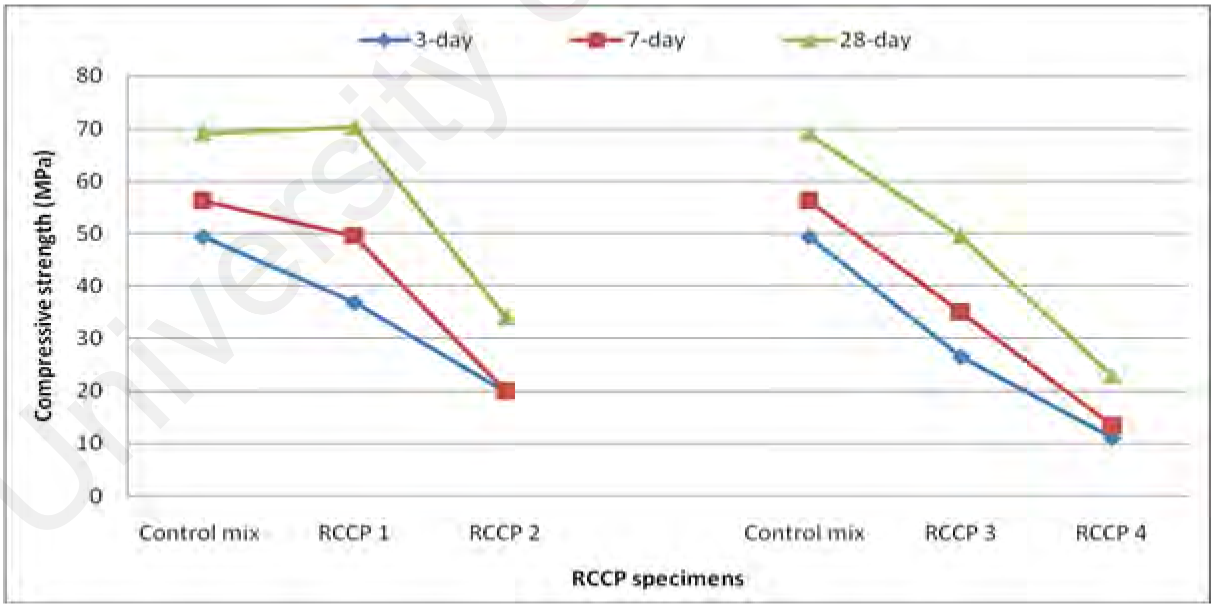


Figure 2.12: The effect of different contents of FA on the compressive strength of RCCPs (Atiş, 2005)

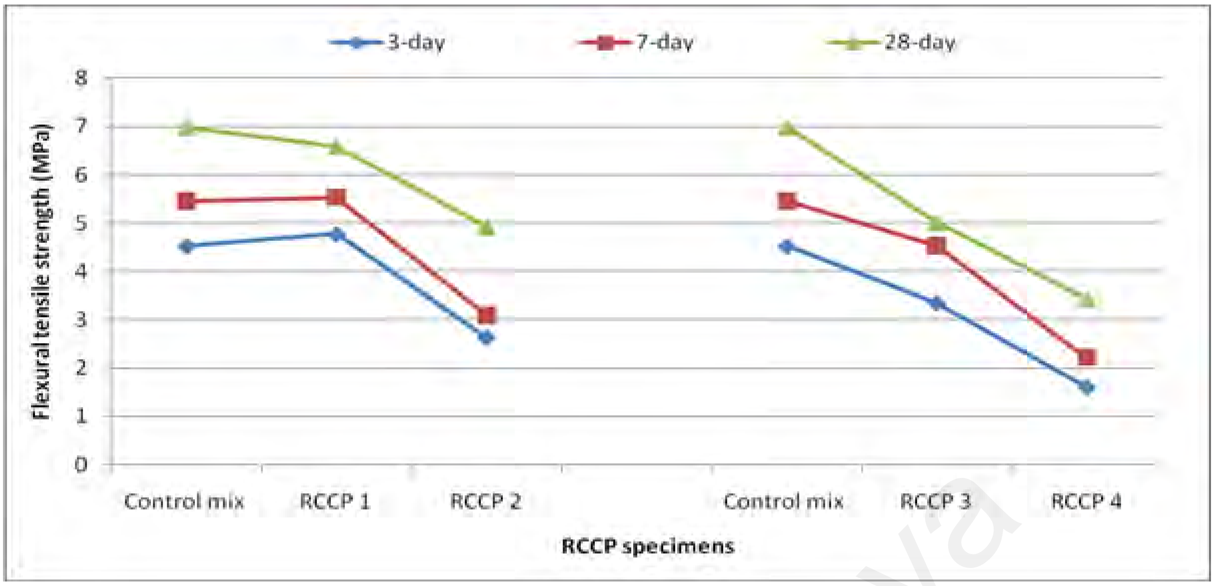


Figure 2.13: The effect of different contents of FA on the flexural tensile strength of RCCPs (Atiş, 2005)

Cao et al. (2000) reported the results of compressive and flexural tensile strengths of RCCPs containing 45% to 95% FA. Figures 2.14 and 2.15 show the mechanical strength of RCCPs with 3, 7 and 28 days curing age. As can be seen, the compressive and flexural strengths of RCCPs containing 45% to 95% FA (RCCP A… RCCP F) are lower than control mix at 3 days. However, the strength of specimens containing 45% and 55% FA (RCCP A, RCCP B) were still comparable at 3 days. It shows, the FA effect is negative at 3 days. At 7 days, the compressive strength of RCCP A and RCCP B were comparable or higher than control mix. It is considerable that the rate of strength gain of RCCPs containing FA is much greater than control mix. It means, the positive effect of FA is tangible after 7 days curing age and the strength of RCCPs developed significantly with longer curing age. Finally, after 90 days curing age, the compressive strength of RCCPs containing 45% to 95% FA were comparable or higher than that of control mix. In addition, the flexural strength of RCCPs containing 45% to 95% FA were higher than control mix. The results show that the positive effect of FA was more beneficial for flexural strength.

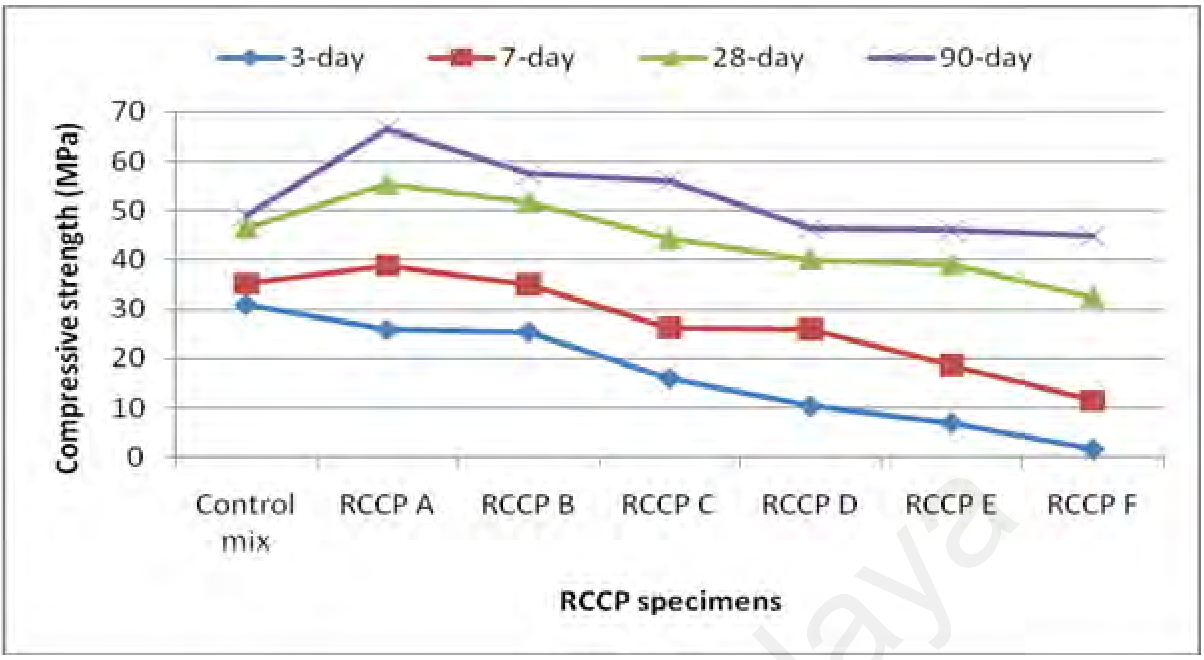


Figure 2.14: The effect of different contents of FA on the compressive strength of RCCPs (Cao et al., 2000)

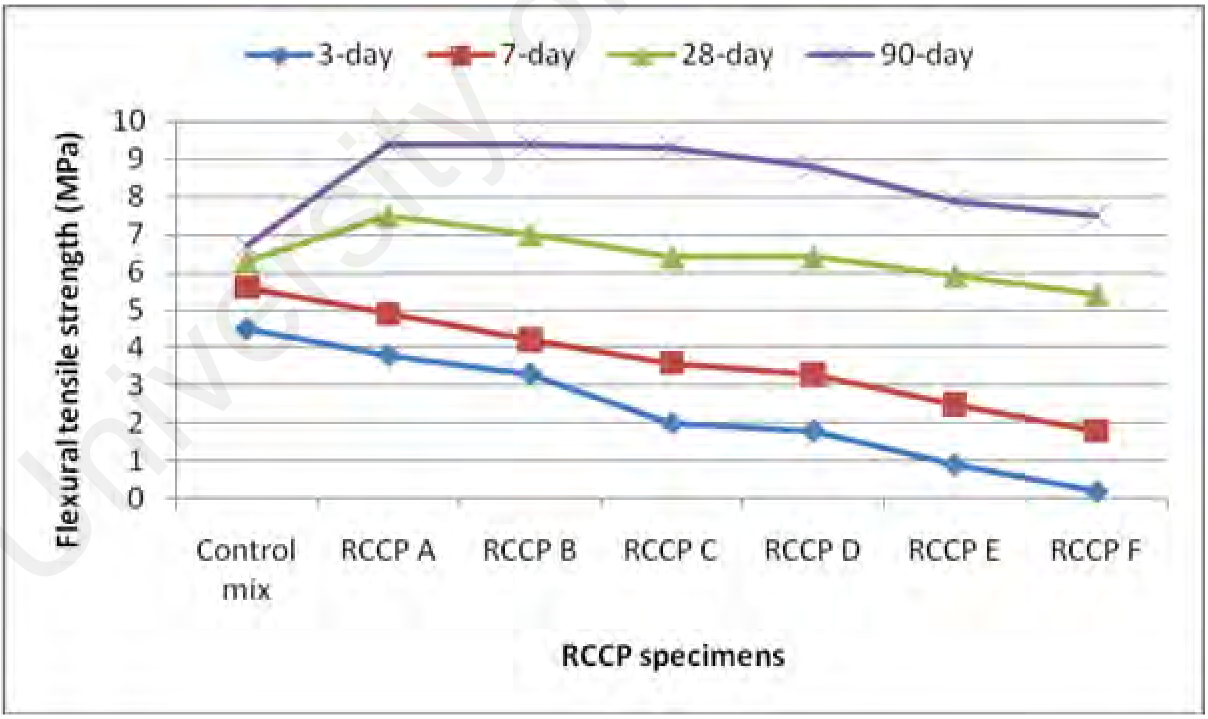


Figure 2.15: The effect of different contents of FA on the flexural tensile strength of RCCPs (Cao et al., 2000)

2.12.1.2 Ground Granulated Blast Furnace Slag

GGBFS is an industrial and a by-product of iron material. It formed by molten iron slag from a blast furnace, when it chilled and immerse in water to get a glassy material. Then a glassy produced material dried and ground into a fine powder. Table 2.9 shows a comparison of the composition of a typical GGBFS and a typical Type I Portland cement.

Table 2.9: Comparison of the composition of GGBFS and type I Portland cement

Chemical Constituents	Type I cement	GGBFS
SiO_2	21.1	40
Al_2O_3	4.6	13.5
CaO	65.1	39.2
MgO	4.5	3.6
Fe_2O_3	2	1.8
SO_3	2.8	0.2
L.O.I.	1.4	0

a. The effect of GGBFS on time span between mixing and compacting of RCCP

Dasmeh et al. (2000) studied on 15, 45, 60, 90, 120 and 150 min time span (TS) between beginning of mixing and compaction in RCCP specimens. Dasmeh et al. (2000) reported that by prolonging the TS between mixing and compacting, the mechanical properties of RCCP specimens have been changed in different modes. In other word, the mechanical properties of RCCPs sometimes have not changed, sometimes got better and sometimes got worse. In other research, Gharavi. (2003) Studied on 15, 30,45,60,90 and 120 min TS between beginning of mixing and compaction in RCCP. Gharavi. (2003) reported by increasing or decreasing TS between mixing and compaction, the strength of RCCP will be decreased. Finally, Gharavi.

(2003) concluded there is an optimal delay time between mixing and compaction of RCCP.

In other study, Karimpour (2010) mad two mixtures containing 150 and 210 kg/m^3 cementitious materials. Karimpour (2010) replaced 25%, 50% and 75% of cementitious materials with GGBFS. He used 30, 60, 120 and 180 min TS between mixing and compaction. Three stages for compressive strength with increasing TS between mixing and compaction is reported. First, by increasing the TS, the compressive strength did not change, then it increased and reached the peak of point. Afterward, compressive strength decreased. This process is due to different phases in cement hydration. Compacting before the crystallized net forming, does not affect the strength. While, compacting when the crystallized net is being forming, causes to increase the strength. However, compacting after the formation of crystallized net, causes to decrease strength. Karimpour concluded by increasing GGBFS in RCCP, maximum compressive strength occurs in long time; in other words, it needs more time to reach peak point. Consequently, this delay could be used to provide more time to work with RCCP.

b. The effect of GGBFS on the mechanical properties, abrasion resistance and Ultrasonic Pulse Velocity of RCCP

Krishna Rao et al. (2016) assessed the effect of GGBFS on the mechanical properties and abrasion resistance of RCCP. Krishna Rao et al. (2016) reported replacement of GGBFS as cement in different contents, decreased strength values of RCCPs at early ages (by 3 days). However, at 7 days and 28 days the strength values increased significantly higher than control mix up to 50% replacement of GGBFS. Also, Krishna Rao et al. (2016) reported that increasing GGBFS has increased abrasion resistance of RCCP at all replacement level. In other study, Krishna Rao et al. (2016) studied on Ultrasonic Pulse Velocity (UPV) testing that conducted on RCCPs containing GGBFS. The amount of GGBFS was changed in variety of 0% to 60% as cement replacement. The range of UPV qualitative rating varies from 3 to 4.5 Km/s (IS 13311). For excellent quality concrete, good quality concrete and medium quality concrete the UPV must be more than 4.5 Km/s, varying between 3.5-4.5 Km/s and between 3.0–3.5 Km/s, respectively. It was good for all RCCPs with GGBFS at first 24 hours, while the quality value improved from good to excellent from 3 days. The UPV for RCCPs with 40% GGBFS replacement was reported the highest in comparison with other mixtures. So,40% GGBFS was reported as optimum cement replacement in RCCP. It should be noted that a good relationship between compressive strength of RCCPs containing 40 to 60% GGBFS and UPV had proposed.

c. The effect of fineness of GGBFS in compressive strength of RCCP

Omid and Iman Makhdoom (2013) investigated the effect of components fineness of GGBFS on strength efficiency of RCCP. The fineness of GGBFS has been reported as vital parameter. In this study, GGBFS with two fineness of 1500 cm^2/g and 2850 cm^2/g were used. Omid and Iman Makhdoom (2013) reported a more improvement in compressive strength of RCCPs which made with slag fineness of 2850 cm^2/g in comparison with slag fineness of 1500 cm^2/g at all ages. This result is in agreement with study which has been done by Binici et al. (2007). This study proved that increase in fineness of GGBFS causes more pozzolanic activity for GGBFS.

2.12.1.3 Rice Husk Ash

RHA is a by-product material from the combustion of rice husk. The ash content is around 18-22% by weight of the rice husks. India is the major rice producing country and its annual paddy production for the year 2014 has been calculated as about 154.5 million tonnes, which produces approximately 31 million tonnes of rice husk that is quite very high (Alex et al., 2016). Rice husk contains about 40% cellulose, 30% lignin group and 20% silica. Therefore, good quality concrete with reduced porosity and reduced $Ca(OH)_2$ can be made due to large amount of silica in RHA (Chindaprasirt et al., 2007). Table 2.10 shows chemical properties of some RHA which have been used in RCCP mixtures.

Table 2.10: Chemical characteristics of some rice husk ash (Villena et al., 2011; Venkatanarayanan & Rangaraju, 2013; Modarres & Hosseini, 2014)

Component (%)	RHA ignition temperature (C)					without temperature control	Low-carbon RHA	high-carbon RHA
	500	600	700	800	900			
SiO_2	85.21	86.11	87.53	87.37	87.49	62.96	92.46	88.50
AL_2O_3	0.51	0.44	0.48	0.55	0.55	22.73	0.26	0.02
Fe_2O_3	0.18	0.19	0.18	0.21	0.19	0.21	0.30	0.86
MgO	0.28	0.29	0.30	0.31	0.32	0.01	0.38	0.34
CaO	1.11	1.18	1.22	1.24	1.25	0.26	1.63	0.48
Na_2O	1.21	1.27	1.29	1.28	1.29	-	1.24	1.19
SO_3	1.33	1.39	1.38	1.40	1.38	0.04	0.11	0.02
K_2O	2.95	3.08	3.15	3.17	3.18	0.45	-	-
Carbon	-	-	-	-	-	-	0.54	>5.00
LOI	6.52	5.25	3.69	3.62	3.56	12.76	-	-

The potential use of RHA has been investigated by some researchers. It has been used, successfully as active filler in hot mix asphalt and as cement replacement in conventional concrete mixtures (Rahman et al., 2014). Some researchers have reported that the use of RHA as a partial cement replacement in concrete by 10% to 20% (by weight of cement) has superior performance characteristics compared to typical concrete (Alvarez, 2006; Habeeb & Mahmud, 2010). Also it has been used in such applications as RCCP (Coutinho, 2003; Kajorncheapunngam & Stewart, 1992; Villena et al., 2011). RHA resulting from the burning of rice husks at control temperatures have physical and chemical properties that meet ASTM Standard C 618-94a. In other words, chemical compositions of RHA are affected by burning process and temperature.

Silica content in the ash increases with higher the burning temperature. At burning temperatures of 550^0C – 800^0C, amorphous silica is formed, but at higher temperatures crystalline silica is produced (Alvarez, 2006). Past researches have shown that the quality and quantity of silica in RHA can significantly change the properties of concrete (Mehta, 1978; James & Rao, 1986; Mehta & Montiero, 2006). It should be noted, ASTM C618:2003 restriction, i.e. for a material to be classified as pozzolan, it should has SiO_2 minimum of 70% and loss of ignition (LOI) a maximum of 6%.

a. The effect of RHA in RCCP

Modarres and Hosseini (2014) worked on RCCP containing RHA as cement replacement at varying amounts of 21% and 36%. Using RHA (at 700 ^0C ignition temperature) as cement replacement in RCCP resulted in (1) increases the optimum moisture content because of the cancellous structure of the RHA and reduced the maximum dry density (2) replacement of 21% RHA as cement had positive effects on the material's flexibility, while the energy absorbency of material decreased by increasing the RHA content by 36% (3) the RCCP mix with 21% RHA had comparable fatigue life to typical RCCP. However, increasing the RHA by 36% had negative effects on the fatigue behavior of RCCP. Therefore, the addition of RHA by 21% showed positive results in RCCP.

In other study Villena et al. (2011) assessed the application of RHA in RCCP as aggregate replacement. In this study 5% RHA on a mass basis was used. They reported addition of RHA lead to significant improvement in RCCP. Replacement RHA as aggregate caused greater optimum moisture and water demand. Replacement 5% RHA as aggregate in RCCP lead to significant improvement in RCC's mechanical strength. The compressive strength, flexural strength and modules of elasticity increased by more than 135%, 60% and 70%, respectively. In addition, using 5% RHA as aggregate decreased the usage of cements and lead to decrease in the quantity of necessary mineral aggregates in RCCP. It should be noted, the consumption of RHA in the construction of RCCP in rice producing region can contribute to the environmental management of the rice production's commodity chain.

2.12.1.4 Silica fume

Silica fume is an ultrafine material with spherical particles less than 1µm in diameter. It is one of the commonly used mineral additive in RCCP mixtures. It has a drying effect on the fresh mixture, because the high surface area of silica fume particles affecting the mobility of water within concrete, so segregation and bleeding of concrete are virtually eliminated. Moreover, silica fume addition to a dry mix such RCCP can result in a more uniform distribution of water during the mixing process (Marchand et al., 1996).

Researchers reported an improvement for strength, density, permeability and frost resistance by using silica fume in RCCP (Naik et al., 2001; Gauthier & Marchand, 2005; Pigeon & Marchand, 1996). These improvements resulting from addition of a very fine powder to the cement paste mix and the pozzolanic reactions between the silica fume and free calcium hydroxide in the paste (Detwiler & Mehta, 1989).

Figure 2.16 shows the Photomicrograph of Portland cement grains, silica fume particles and FA. It should be noted that ACI 234R, guide for the use of silica fume in concrete, estimates that for a 15 percent silica fume replacement of cement, there are approximately 2,000,000 particles of silica fume for each grain of Portland cement (Holland, 2005).

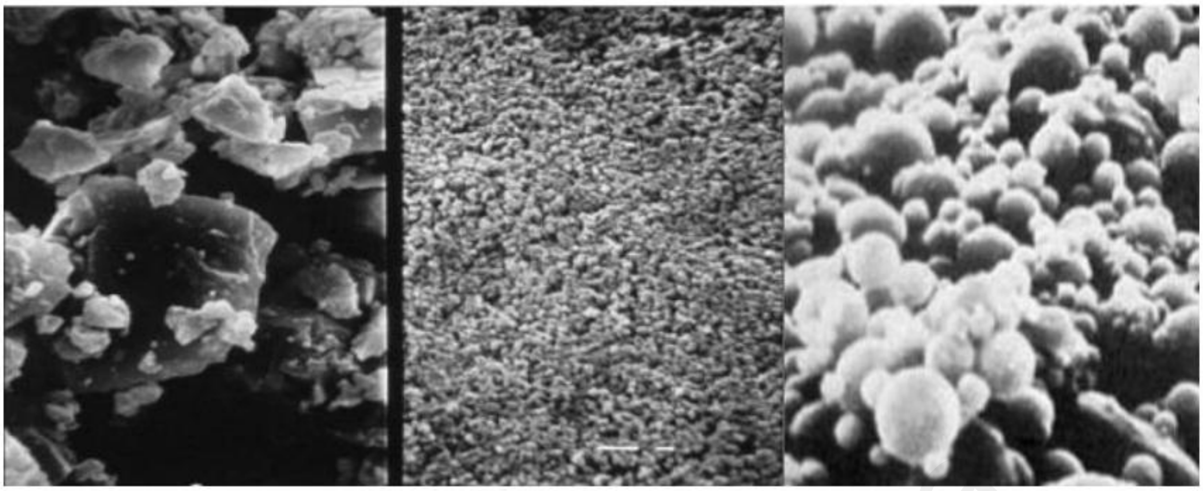


Figure 2.16: Photomicrograph of Portland cement grains (left), silica fume particles (middle) and fly ash. The longer white bar in silica fume side is 1 micrometer long (Holland, 2005; Rossow, 2003)

a. High strength RCCP with silica fume

Use of silica fume recommended in high strength RCCP (e.g. 28-day compressive strengths larger than 65MPa). Marchan et al. (1997) reported that RCCP mixtures with silica fume which have shown compressive strength greater than 65 Mpa at 28 days. In other study Ribeiro and Almeida (2000) investigated that the high performance roller compacted concrete (HPRCC). They showed high compressive strength about 133 Mpa at 28 days can be obtained easily. Some parameters were reported as important notes to get HPRCC, including: very resistant coarse aggregate, low dosage of sand and water, using high compaction energy to make concrete and using silica fume. It should be noted the maximum amount of silica fume in the RCC mixture is usually limited to 10% of cement (Marchand et al., 1997; Vahedifard et al., 2010; Bettencourt Ribeiro & De Almeida, 2000).

Using of silica fume with superplasticizer in RCCP can provide good improvements in strength, density, and resistance to freeze and thaw (Naik et al., 2001). In this way Rindal and Horrigmoe (1993) consumed silica fume in RCCP with combinations of superplasticizer and air-entrained admixture. Rindal and Horrigmoe reported using silica fume with combinations of superplasticizer and air-entrained lead to improvement in freeze and thaw resistance of RCCP.

Vahedifard et al. (2010) investigated the effect of silica fume and pumice on the performance of RCCP. In this study 10%, 30% pumice and 10% silica fume used as cement replacement. The results of the VeBe tests showed that the pumice made the specimens more workable, but had a negative impact on both the compressive strength and frost resistance. In contrast, the specimens containing silica fume became drier and less workable. Silica fume enhanced both the compressive strength and frost durability of the RCCP mixes. However, the workability RCCP with silica fume is less than that of normal RCCP.

2.12.2 The recommended supplementary cementitious materials amount as cement replacement to be used in RCCP

In a nutshell, by considering all the important points from above discussion, the optimal value for FA, GGBFS, Silica fume and RHA as cement replacement in RCCP are shown in the Figure 2.17.

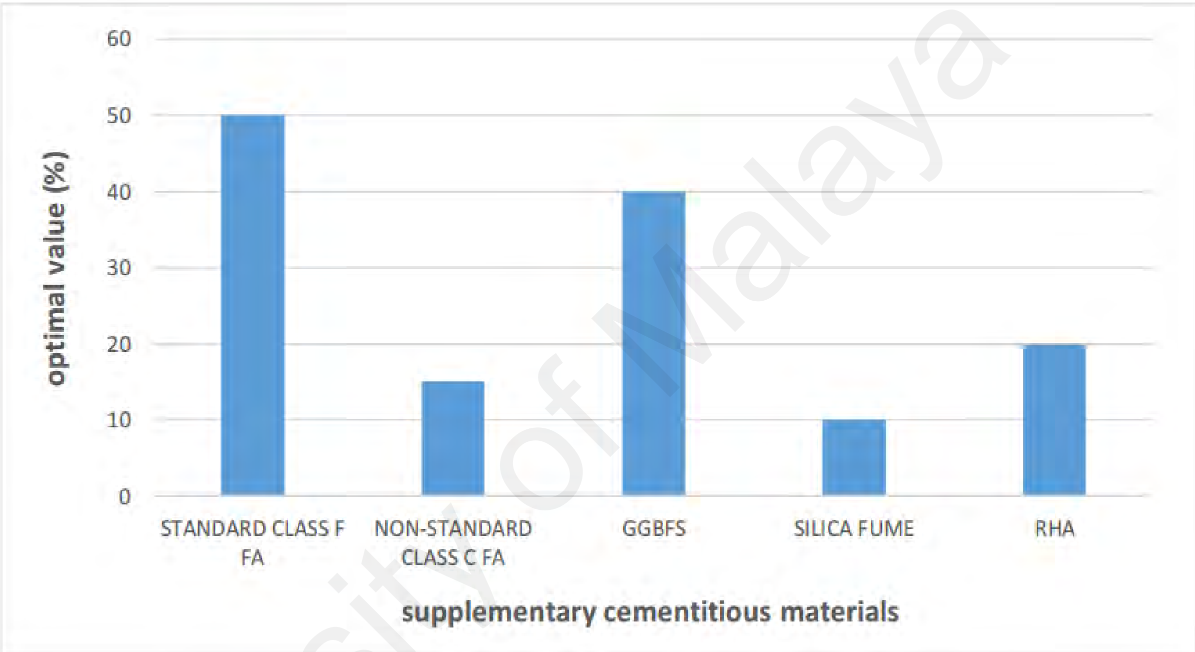


Figure 2.17: Recommended supplementary cementitious materials as cement replacement in RCCP

CHAPTER 3. MATERIAL CHARACTERISTICS AND EXPERIMENTAL PROGRAM

3.1 Materials

For all the mix proportions used this study, ASTM Type 1 cement was used. In addition, Ground Granulated Blast Furnace Slag (GGBFS) and Fly ash (FA) as supplementary cementitious materials and limestone powder as filler were also used.

Crushed granite as normal coarse aggregate was used. Fine aggregate used was local mining sand. Lightweight Expanded Clay Aggregates (LECA) which imported from an Iranian factory was used to replace coarse aggregate. For some mixtures a superplasticizer with different dosage was used.

3.1.1 Cement and supplementary cementitious materials

The ordinary Portland cement used was "Tasek Cement" obtained from Malaysia Tasek Corporation Berhad which conforms to MS522, part-1:2003 with a 7- and 28-day compressive strength of 36 and 48MPa. Specific gravity of cement used was 3.14 and its specific surface area was 3510 cm^2/g. FA with specific gravity of 2.37 was used. GGBFS with specific gravity of about 2.87, bulk density in the range of 1180-1250 kg/m^3 and specific surface area of 4.12 m^2/g was used. In addition, limestone powder with 92% < 75μm, 85% < 45μm and Blaine's specific surface area of 7270 cm^2/g, was used as filler and as part of the fine aggregate. The chemical properties of the cement, FA, GGBFS and limestone powder are shown in Table 3.1.

Table 3.1. Chemical composition and LOI of OPC, FA, GGBFS and LSP (% by mass)

Chemical composition	OPC	FA	GGBFS	Lime Stone Powder
Cao	63.40	1.00	49.76	53.23
Sio_2	19.80	64.60	29.35	0.21
Al_2O_3	5.10	20.90	11.72	-
Fe_2O_3	3.10	4.00	0.52	0.16
MgO	2.50	0.66	4.20	2.54
SO_3	2.40	0.30	2.09	0.35
K_2o	1.00	1.20	0.46	0.03
Na_2O	0.19	0.32	-	-
LOI	1.80	5.10	-	41.55

3.1.2 Water

Potable water, free from impurities and chemical contaminants was used for all mixes.

3.1.3 Aggregate

3.1.3.1 Coarse aggregate

Crushed coarse aggregate used had a maximum nominal size of 19 mm and 12.5 mm with saturated-surface-dry (SSD) specific gravity of 2.62 and water absorption of 0.67%. The coarse-to-fine aggregate ratio was chosen 1.2 to get workable, high strength and durable RCCP. It should be noted that the grading of aggregate was in the range of ACI and PCA limits as presented in chapter two (Section 2.1.2).

3.1.3.2 Fine aggregate (Sand)

For all concrete mixtures, sand from a local mining site was used and its physical properties include a fineness modulus (represents the mean size of the particles in sand) of 2.69, SSD specific gravity (the specific gravity of a solid is the ratio of its mass to that of an equal volume of distilled water at a specified temperature) of 2.61, water absorption of 1.5% and maximum particle size of 4.75 mm.

3.1.3.3 Lightweight expanded clay aggregates

Lightweight expanded clay aggregates (LECA) is imported from an Iranian factory. Any aggregate with a particle density of less than 2.00 kg/m^3 or a dry loose bulk density of less than 1200 kg/m3 is defined as lightweight aggregate (Clarke, 2014). Physical properties and sieve analysis of the LECA are indicated in table 3.2.

Table 3.2. Physical properties and sieve analysis of LECA

Physical properties	LECA
Specific gravity	1.52
Bulk density (kg/m3)	780
Water absorption (24 h) (%)	17.68
Grading	
Sieve size (mm)	
12.5	100
9.5	98.9
8	89.2
6.3	54.8
5	16.5
4.75	13.3
3.36	1.8
2	1

3.1.4 Superplasticizer

The superplasticizer (SP) used is Sika Viscocrete-2192 from Sika Company. This SP is in conformity with EN 934-2 and meets the requirements of BS EN 934-2. It is a highly effective liquid SP for the production of free flowing concrete for promoting high ultimate and early strengths. The SP used is a modified polycarboxylate type super plasticizer. The recommended dosage for medium workability and special applicants such as self-compacting of ultra-high strength concrete is 0.1-1.0% and 1.0-2.0% by weight of cement, respectively.

3.2 Test Methods and Measured Properties

Laboratory testing program was aimed at measuring the properties of workability, strength and stiffness, durability, and microstructure of RCCP. Modified Vebe test and slump test were employed to determine the consistency of RCCP and workability of Normal Vibrated Concrete (NVC) specimens, respectively. Hardened properties of concretes were measured by compressive strength, splitting tensile strength and flexural tensile strength tests at 1, 7 and 28 days. The stiffness (or modulus) of concrete was measured by the modulus of elasticity test and ultrasonic pulse velocity (UPV) test. Absorption (at initial and final stages) and porosity of concrete were measured for the durability evaluation. Field Emission Scanning Electron Microscope (FESEM) was used for the microstructure assessment. The capability of heat transfer in RCCP was measured by specific heat capacity and thermal conductivity test.

3.2.1 Test on fresh concrete

3.2.1.1 Consistency and workability

The workability of conventional concrete was determined by the slump test, ASTM C143-03. However, the Vebe test, ASTM C1170-06, was employed to measure the consistency of concrete since RCCP is a “zero-slump” concrete. Two procedures are provided by ASTM C1170-06; Procedure A for testing concrete of very stiff to extremely dry consistency or when the Vebe consistency by procedure B is 30 s or greater. In Procedure A the modified VeBe time is defined as the vibration time required for a ring of mortar to form between the surcharge weighing 22.7 kg and the container wall. However, Procedure B should be considered for testing concrete of stiff to very stiff consistency or when Vebe time by procedure A is less than 20 s. In Procedure B the modified VeBe time is defined as the vibration time required for a ring of mortar to form between the surcharge weighing 12.5 kg and the container wall.

For dry concretes, relative density or compactibility, cohesion, and tendency to segregate are quite important properties (Juvas.,1994). According to ACI 116R-90, the workability is defined as “that property of freshly mixed concrete which determines the ease and homogeneity with which it can be mixed, placed, consolidated, and finished”.

3.2.2 Test on hardened concrete

Compressive strength

A compressive strength test was carried out on cylindrical specimens with 100 mm diameter and 200 mm height. Three specimens of each mixture were tested at 1, 7 and 28 days according to ASTM C39-02. The freshly-mixed concretes were molded in cylindrical molds by using an electric vibrating hammer equipped with a shaft and circular plate according to ASTM C1435-08 (see Figure 3.1and Figure 3.2).

Figure.3.1: Electric vibrating hammer (right) and circular and rectangular plate (left)

Fig.3.2: Compaction of RCCP specimens by electric vibrating hammer

Splitting tensile strength

A splitting tensile strength test was performed on cylindrical specimens with 100 mm diameter and 200 mm height according to ASTM C496-11.

Flexural tensile strength

A flexural tensile strength test was carried out on prism specimens with dimensions of 100 × 100 × 500 mm according to the relevant ASTM C78-10 standard. The preparation of the prism specimens was made by using an electric vibrating hammer equipped with a shaft and rectangular plate. The prism specimens were cast in three layers, and each layer was fully compacted until mortar was formed on the top surface. The specimens were demolded one day after casting, and cured under water after demolding until the times of testing. Three samples were prepared for each mixture.

3.3 Porosity

Three cylindrical specimens with 100 mm diameter and 200 mm height aged for 28 days were used in the porosity test. One piece 5cm thick was cut for each specimen. Afterward, the 5cm thick samples were dried in an oven at 105°C for approximately 24 hours to remove moisture. After drying, the samples were placed in a vacuum desiccator (Figure 3.3). In this step, both end faces of the samples had to be exposed.

The desiccator was sealed and the vacuum pump started. The pressure decreased to 700 mm Hg within a few minutes and the vacuum condition was maintained for 3 hours. Another container was filled with water. The water stopcock was opened and sufficient water was drained into the vacuum desiccator to cover the samples. In this step, air was not allowed to enter the desiccator through the stopcock. Next, the water stopcock was closed and the vacuum pump was allowed to run for one additional hour. Finally, the vacuum line stopcock was closed and the pump was turned off to allow air to re-enter the desiccator. The samples were soaked in water for 18±2 hours. For water to fill all accessible pores of the concrete sample, it is essential to empty the pores of air and water (Khan., 2004). A test method based on evacuating air from the oven-dried samples and then allowing the water to fill the pores under vacuum to reach full saturation is also recommended (Rilem., 1984). The amount of water penetrating a sample is a measure of porosity and is calculated as follows:

$$P = \frac{B-A}{A} \times 100 \qquad \text{(Eq.3.1)}$$

Where **P** is the porosity (%), **A** is the oven-dry weight and **B** is the saturated surface dry weight.

Figure 3.3: Porosity test set-up

3.4 Water absorption

Water absorption values were measured in accordance with ASTM C642-06. The water absorption test was conducted on 100 × 200 mm cylinder. The saturated surface dry specimens were dried in an oven at 105 ± 5 ℃ for 24 hrs. Dry weight (A) was then recorded. Afterward the specimens were immersed in water at 20 ℃ until they achieved a constant weight (B). The absorption at 30 min (initial absorption) and at 72 hrs (final water absorption), when the difference between two consecutive weights was almost negligible, were calculated by the following formula:

$$\text{Water absorption (\%)} = \left[\frac{\mathrm{B-A}}{\mathrm{A}}\right] \times 100 \quad \text{(Eq.3.2)}$$

3.5 Ultrasonic pulse velocity test

Ultrasonic Pulse Velocity (UPV) is a non-destructive method that checks the quality of concrete, homogeneity and compressive strength of existing structures (Jones & Fącąoaru.,1969; Rao et al., 2016). There are two ways of making ultrasonic measurement (IS 13311 (Part I)-1992) 1) By direct Transmission 2) By Propagation along the surface. The direct Transmission was considered for this research. The principle of this test was that the velocity of sound in a solid material like concrete. The UPV test was performed on 100 mm cubes as per BIS 13,311 (Part 1)-1992. In this test, the frequency of the transducer was kept as 54 kHz. The time the pulses take to travel through the concrete specimen was recorded, and then the velocity was computed using the equation below:

$$V=\frac{\mathrm{L}}{\mathrm{T}} \quad \text{(Eq.3.3)}$$

V = Pulse velocity (m/s); L = Length of travel (m); T = effective time (s)

3.6 Modulus of Elasticity

The Static modulus of elasticity test was conducted in accordance with ASTM C469-02. The modulus of elasticity is one of the fundamental parameters in structural design to determinate strain and displacements of concrete that tested at 28 days. The cylinder specimens of 150 mm diameter and 300 mm height were placed on compression testing machine and uniform load was applied till the final load failure. For strain calculation dial gauge readings divided by gauge length and for stress, load applied divided by area of cross-section of samples. For finding modulus of elasticity of samples, the deformation of different loads was plotted graphically against the stress. In the stress-strain curves, the modulus of elasticity was determined from the slope of the initial tangent modulus. Three cylinders were prepared for each test. The end surface of all specimens was grinded to ensure uniform load distribution over the specimen surfaces.

3.7 Field Emission Scanning Electron Microscope (FESEM) Test

Electron microscope has the ability to resolve objects ranging from nano-metre to micro-metre. However, a light microscope that has a magnification in the range of 1000 and resolution of 200 nm. In addition, electron microscope can be used as a diagnosis tool for nano- and micro-scale cracking on concrete (Balendran et al., 1998). The Field Emission Scanning Electron Microscope (FESEM) is an advanced microscope that offers increased magnifications and the ability to observe fine features with a lower voltage than typical Scanning Electron Microscope (SEM) (Handbook of analytical methods for materials, 2015). In this study the FESEM test was used to detect entrapped air voids and compaction voids in RCCP specimens. Figure 3.4 shows FESEM machine.

Figure 3.4: Field Emission Scanning Electron Microscope test

3.8 Thermal conductivity Test

Thermal conductivity test was performed on cylindrical specimens (100mm×200mm) at the age of 28 days. The samples were oven dried for 24 hours in degree of 100 ± 5 C to remove internal moisture. KD2-PRO analyzer with TR1 needle sensor was used for testing and TR1 sensor (2.4 mm in diameter and 100 mm in length) is capable to measure thermal conductivity in the range of 0.1 W/m.°K to 4 W/m.°K. A pilot pin was inserted to the uncured specimens to prepare the hole in the size of TR1 sensor. The relatively long read times of sensor (10 minutes reading and 15 minutes interval) contribute to minimize errors caused from the large diameter needle. The contact between needle and specimen was ensured by using thermal grease on the hole (see Figure 3.5).

(a) (b)

Figure 3.5: (a) Thermal conductivity measurement by KD2-Pro (b) Preparing a hole to insert TR1 sensor

The principle of KD2-PRO analyzer involves heating the needle for a time and monitoring the temperature during the heating and cooling process. During testing, the ambient temperature was maintained at constant temperature to obtain accurate measurement. In addition, the surface of specimens was wrapped by plastic bag to minimize the effect of ambient temperature. The thermal conductivity can be calculated by the equation below:

$$Q = -kA\frac{\partial T}{\partial x} \qquad \text{(Eq.3.4)}$$

Where Q is Heat flow (W), K is the thermal conductivity (W/m.°K), A is the area to the x – direction (m^2), ∂T is temperature difference (°K) and ∂x is the distance (m).

3.9 Specific heat capacity test

The specific heat capacity measurement was through calorimeter method which was used by Islam and Tarefder (2014). The foam ice box was prepared as a calorimeter to measure the c-value of samples in the present of water as the known c-value material. The temperature changing of the 60.5 °C water was around 1.4 °C in one hour.

One piece of each oven dried sample was cut and kept in room temperature for 24h. The mass and temperature of water as well as the surface temperature and weight of cement-mortar specimens were measured. After that the concrete samples were immersed to the water and the changing temperature was monitored through available thermometer inside the box. Finally, the specific heat of concrete pavement was calculated using the following equation:

$$C_c = \frac{m_w\, C_w (T_w - T_e)}{m_c\, (T_e - T_c)} \qquad \text{(Eq.3.5)}$$

Where C_c and C_w are the specific heat of concrete samples and water (kJ/kg.°K), m_s and m_w are the mass of concrete and water (kg) and T_c, T_w and $T_e$are the concrete, water and equal temperature, respectively (°C).

Further, the law of mixture as below can be used to calculate The specific heat capacity of mixture as a function of its component (Othuman & Wang, 2011):

$$C_p = \sum F_i C_{pi} \qquad \text{(Eq.3.6)}$$

Where C_p is the specific heat of mixture (kJ/kg.°K), C_{pi} is the specific heat of each component and F_i is the weight fraction of each component.

3.10 Research design

Two methods are usually used for the mix design of RCCP. The first method is based on the workability of concrete to achieve the required consistency by adjusting water-to-cement ratio (w/c) and sand-to-cement ratio (s/c) (Mardani-Aghabaglou et al., 2013; ACI 325-10). The second method is the maximum density method in which a mix design is based on the maximum dry density of concrete (ACI 211 3R-02; Khayat & Libre 2014). The basic concept in this method is to maximize the packing density of solid materials by adjusting the moisture content. The optimum moisture content is defined as the moisture content corresponding to the maximum density in a moisture content-density curve, and is dependent on properties of the aggregates used and the content of cementitious material (ACI 325-10). For most aggregates, optimum moisture content is found within the range from 5 to 8 percent (Harrington et al., 2010).

The mixtures used in this study were designed based on the soil compaction concept (second method) in accordance with ACI 211.3R.02. For all mixtures, different content of Portland cement by mass of total dry solids was used. The C/F ratio was chosen for RCCP specimens. It should be noted that the grading of combination of coarse aggregate and sand was in the range of ACI and PCA for all mixtures. The NMSA for all RCCP mixtures was limited to 19 mm to prevent from segregation. The preparation of the cylindrical and prism specimens was made by using an electric vibrating hammer equipped with a shaft and rectangular plate. The specimens were cast in three layers, and each layer was fully compacted until mortar was formed on the top surface. The specimens were demolded one day after casting, and cured under water after demolding until the times of testing. Three samples were prepared for each mixture. The objectives of this study were achieved as the flow chart shown below (Figure 3.6):

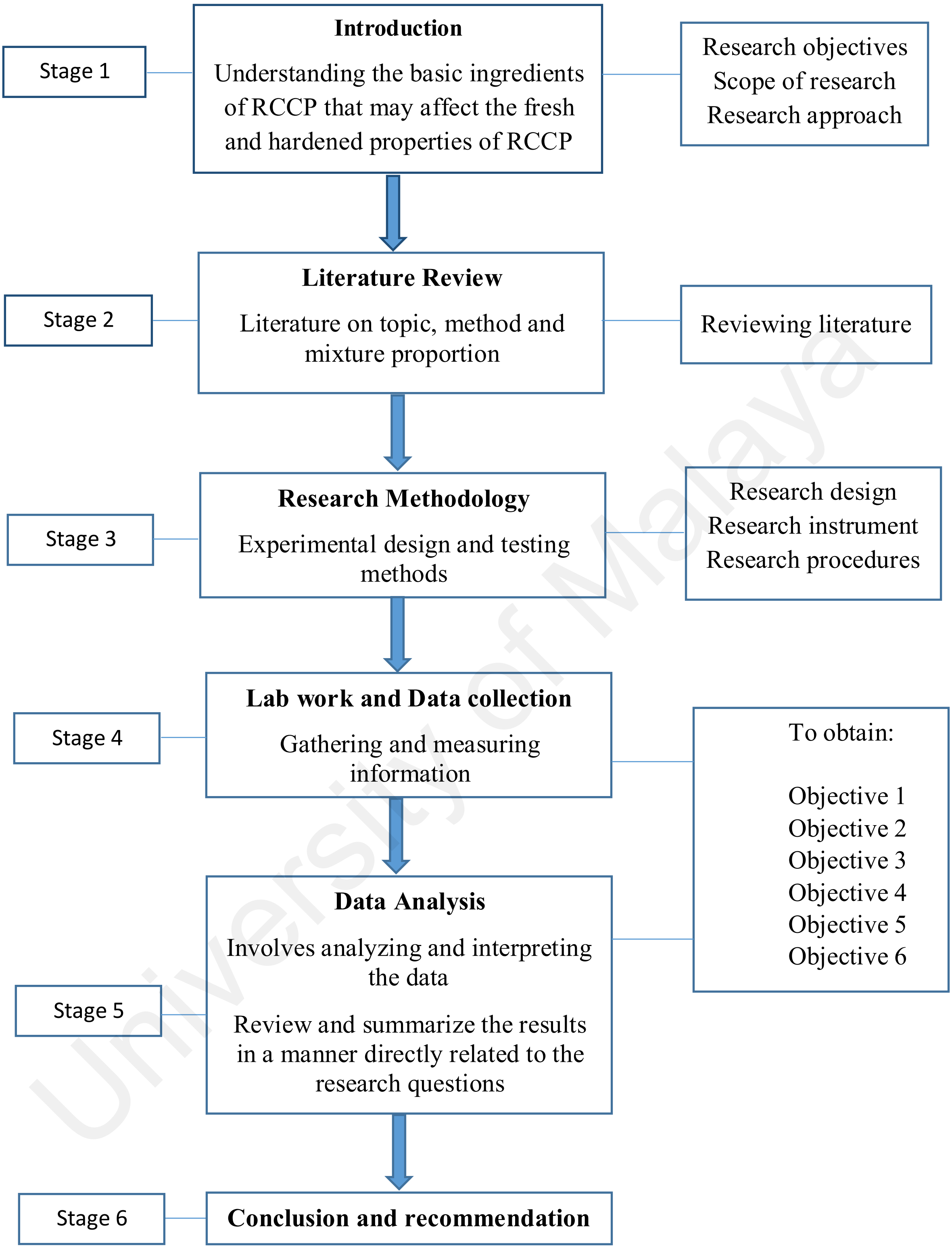


Figure 3.6: Research flowchart of methodology

The research design for different objectives of this study are classified in hereafter sub-sections.

3.10.1 Research design for first objective

In this study, two groups of RCCP were used, containing 9% and 12% Portland cement by mass of total dry solids (204 and 268 kg/m^3), respectively. Each group consisted of C/F ratios between 0.6 and 1.8 (at 0.2 intervals). The grading curves of coarse and fine aggregates were within ASTM C33 standard limits, as shown in Figure 3.7. Moreover, the grading curves of aggregates for RCCP mixtures with different coarse to fine aggregate ratios and with 9% and 12% cement contents were compared with the 0.45 power maximum density curve in Figure 3.8 and Figure 3.9, respectively. In these figures, "A" represents for 9% cement content and "B" denotes for 12% cement content RCCP mixtures. The mix proportions of all concretes are given in Table 3.3.

Table 3.3: Mix proportion details and Vebe test results

Mix No.	Cement		Water to cement ratio	Coarse aggregate (Kg/m^3)	Fine aggregate (Kg/m^3)	Coarse to fine aggregate ratio	Water (Kg/m^3)	Vebe Time (S)
	%	Kg/m^3						
A-9-1	9%	204	0.42	773	1288	0.6	85.6	10-20
A-9-2				916	1145	0.8	85.6	
A-9-3				1030	1030	1	85.6	
A-9-4				1123	937	1.2	85.6	20-30
A-9-5				1202	859	1.4	85.6	
A-9-6				1268	793	1.6	85.6	30-38
A-9-7				1325	736	1.8	85.6	
B-12-1	12%	268	0.42	738	1230	0.6	112.8	10-18
B-12-2				875	1094	0.8	112.8	
B-12-3				984	984	1	112.8	
B-12-4				1074	895	1.2	112.8	18-26
B-12-5				1148	820	1.4	112.8	
B-12-6				1211.5	757	1.6	112.8	26-34
B-12-7				1266	703	1.8	112.8	

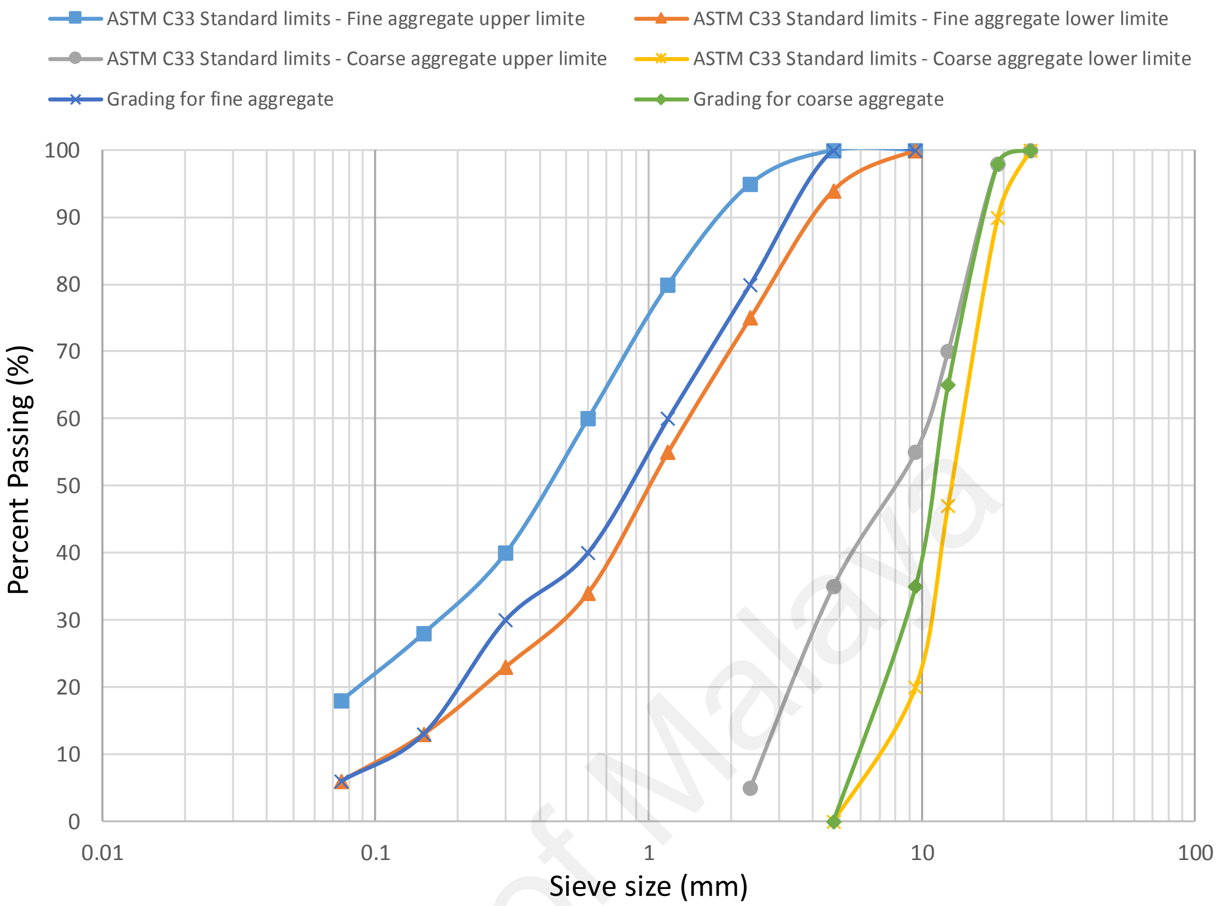


Figure 3.7: Sieve analysis of fine and coarse aggregates compared to ASTM C33 standard limits

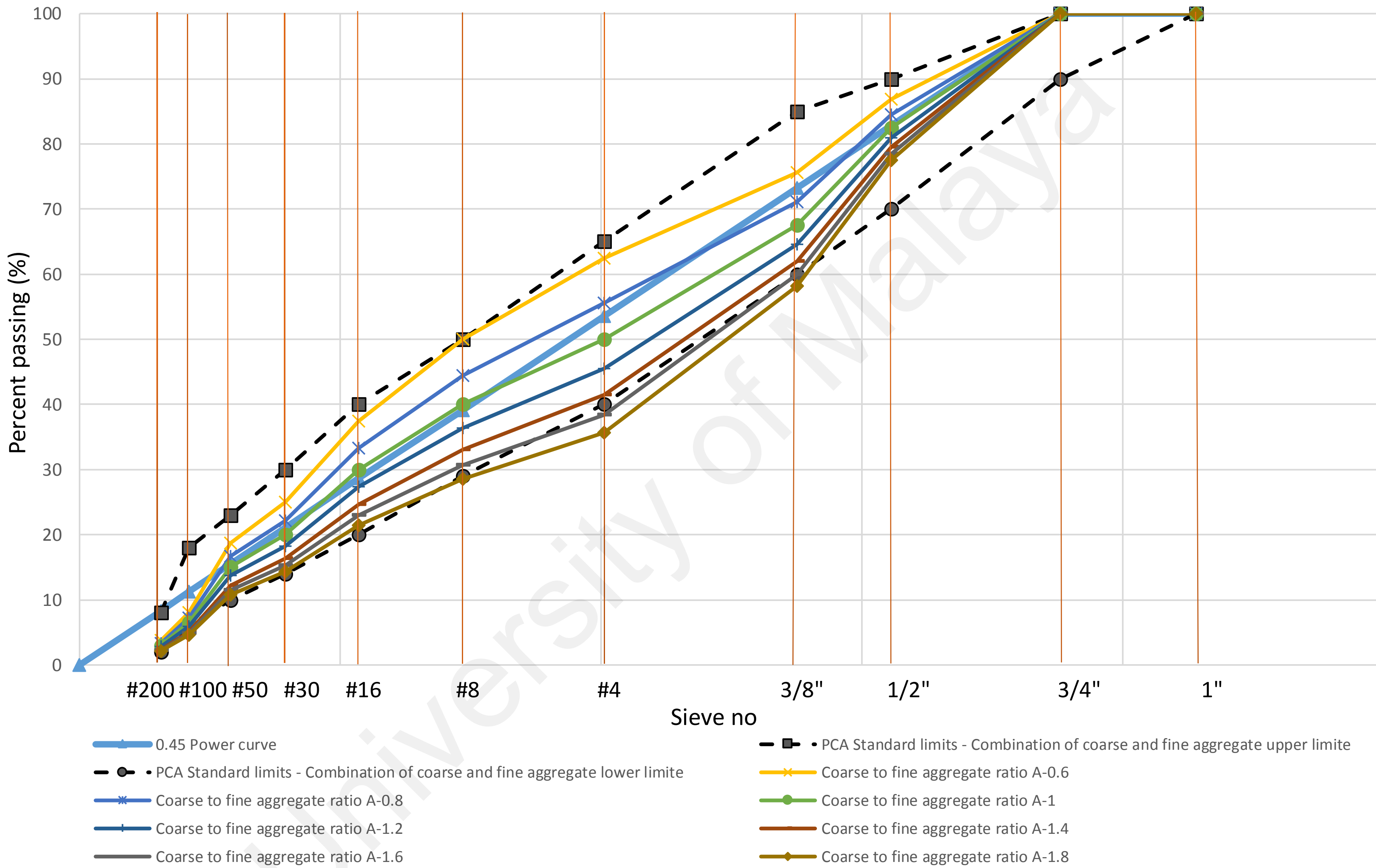


Figure 3.8: Sieve analysis of aggregates with different coarse to fine ratios for 9% cement RCCP and comparison with 0.45 maximum density curve

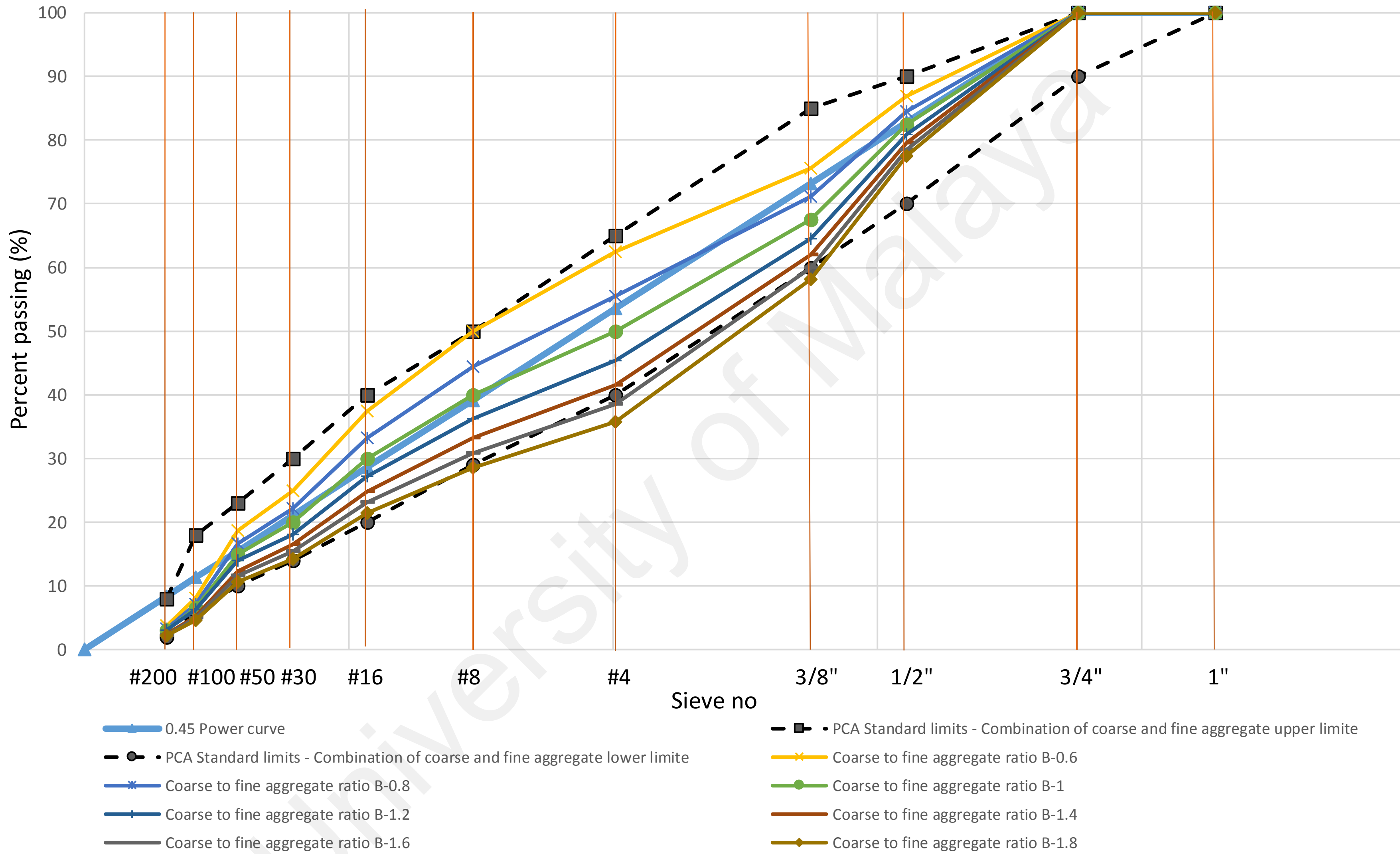


Figure 3.9: Sieve analysis of aggregates with different coarse to fine ratios for 12% cement RCCP and comparison with 0.45 maximum density curve

3.10.2 Research design for second objective

For all mixtures, local mining sand was used. Grading of this sand (low fines content sand) is shown in Figure 3.10. Crushed coarse aggregate used in this investigation had a maximum nominal size of 19 mm. It should be noted that the grading of coarse aggregate is in the range of ACI and PCA for all combination of coarse aggregate with standard sand and low fines content sand.

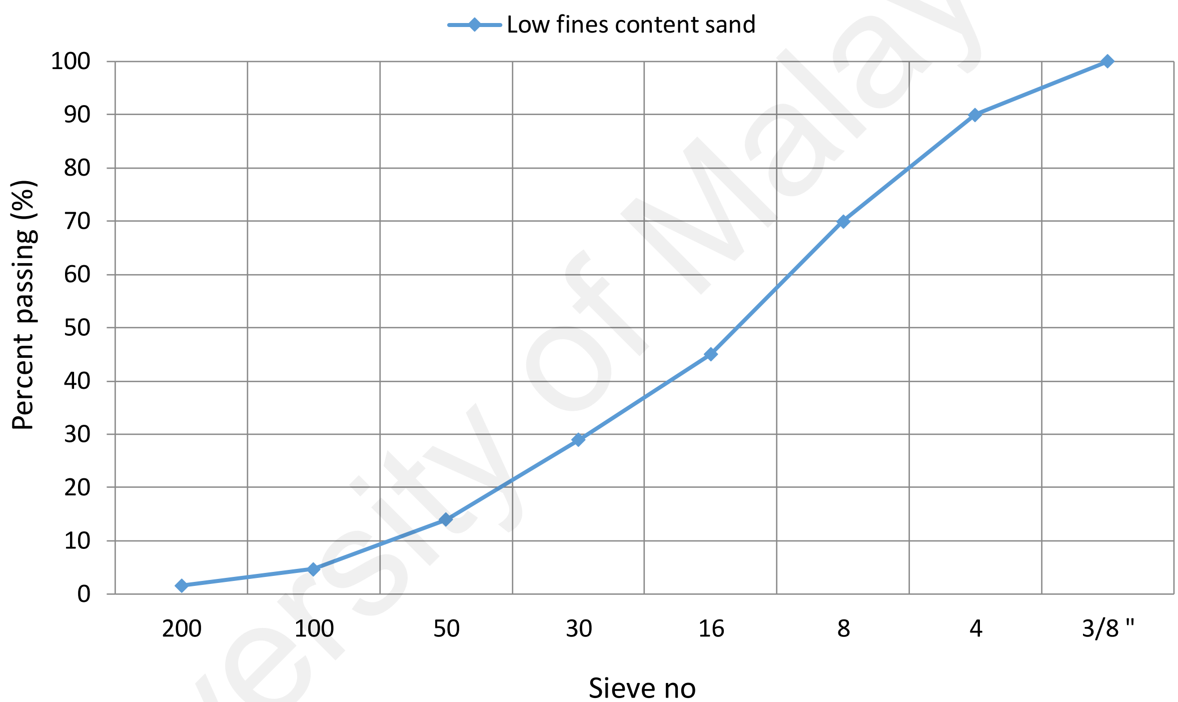


Figure 3.10: Sieve analysis for low fines content sand

Lime stone powder (LSP) is one of the most important raw material for the construction industry. It is reported that LSP has filling effect, active effect and accelerating effect during hydration process under the condition of high temperature steam curing (Liu et al., 2012; Shuhua & Peiyu, 2008). In addition, the beneficial influences of LSP on the fresh and hardened properties of concrete have been reported (Hesami et al., 2016; Lollini et al., 2014; Avila-López et al., 2015; Courard & Michel, 2014). The chemical properties of the LSP that is used in this study explained in this chapter (3.1.1). In this study the filling effect of LSP was considered. The major content of LSP particle size passes from sieve #100 and #200 that provides good particle size distribution with low fines content sand. The particle size distribution of LSP is presented in Figure 3.11. The gradation of standard sand, low fines content sand and limestone modified sand with 6% LSP are shown and compared with PCA standard limitation in Figure 3.12. As can be seen, the values for low fines content sand appear out of lover limit of standard for sieves #8, #50, #100 and #200. However, those values for low fines content sand+ 6% LSP is comparable with standard sand. These differences are highlighted in Table 3.4.

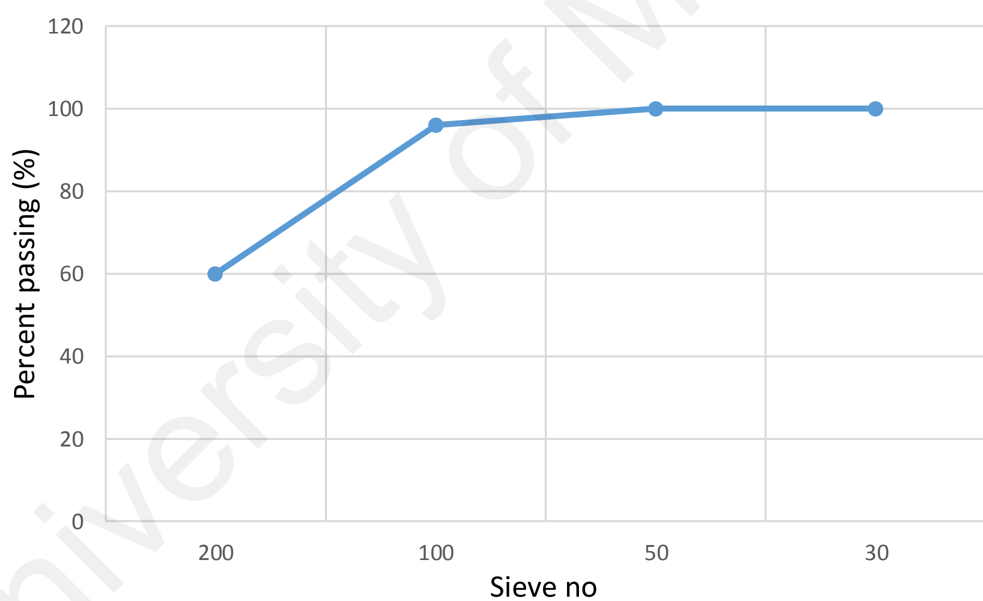


Figure 3.11: Sieve analysis of Lime Stone Powder (LSP)

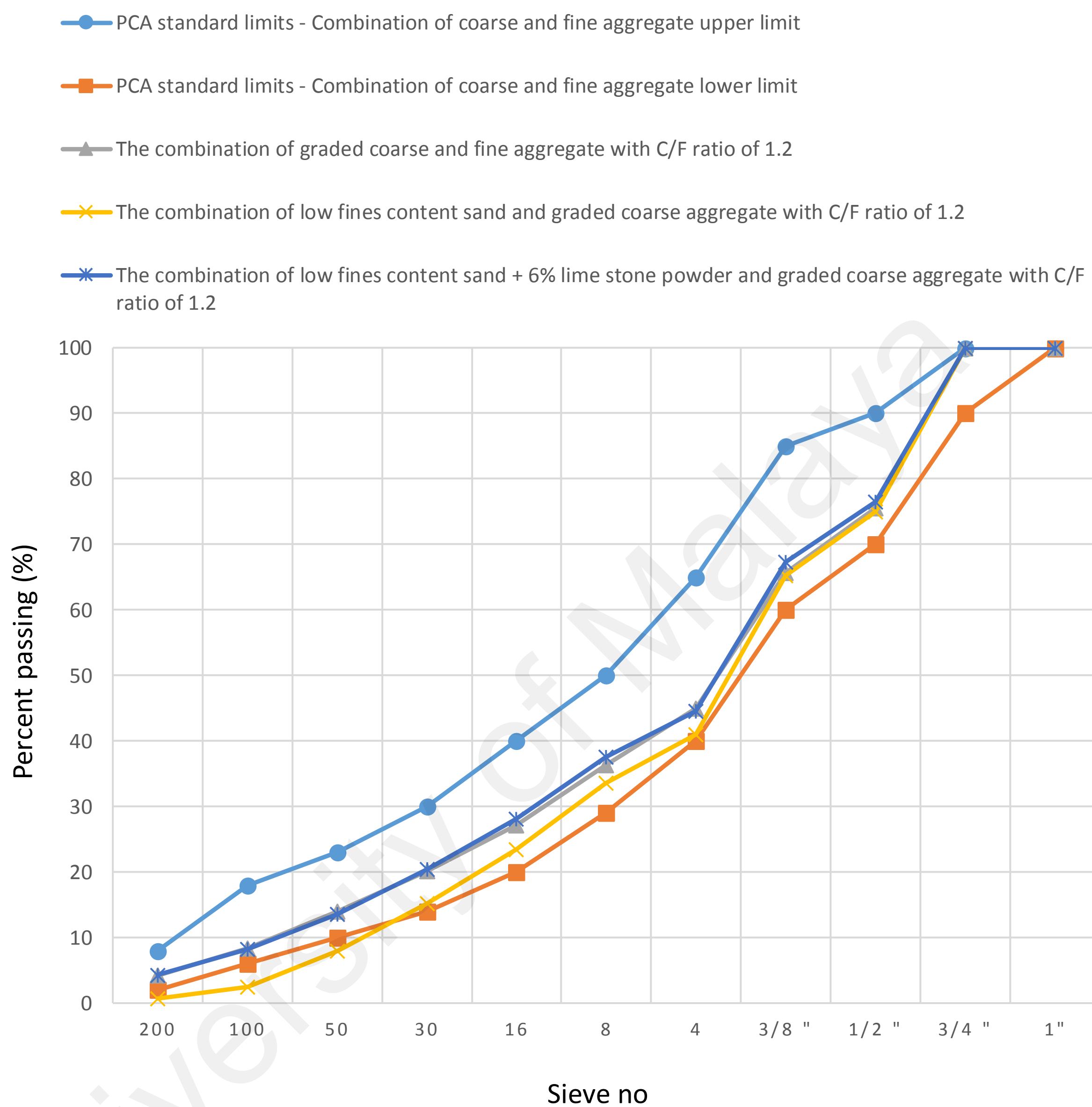


Figure 3.12: Sieve analysis of coarse and fine aggregates compared to PCA standard limits

Table 3.4: The differences between standard sand and low fines content sand

Sieve No	ACI	PCA	Percent passing for standard sand	Percent passing for low fines content sand	Percent passing for low fines content sand+6% LSP
#8	35-55	29-50	36	33	37
#50	8-20	10-23	15	8	13.5
#100	6-18	6-18	11	2.5	8.2
#200	2-8	2-8	4.5	0.7	4.3

In this study, two groups of RCCPs containing 12% and 15% OPC by mass of total dry solids were used. For each cement content three groups of aggregates containing 1) well graded coarse aggregate + standard sand, 2) well-graded coarse aggregate + low fines content sand and 3) well-graded coarse aggregate + low fines content sand + 6% LSP were used. The mix proportions of all RCCPs are given in Table 3.5. In this table, 'A-12' and 'B-15' stand for "RCCPs with 12% cement" and "RCCPs with 15% cement", respectively. Also, 'SS', 'LFS' and 'LMS' stand for "standard sand", "low fines content sand" and "limestone modified sand", respectively.

As can be seen, water-to-cement ratio for all mixes except mixes containing LSP is fixed to 0.40. LSP is very fine and significantly increases surface area of aggregate when it is used in concrete mixture. Therefore, the water content increased for RCCP containing LSP to get a satisfactory workability.

Table 3.5: Mix proportion details and Vebe time results

<table>
<tr><th rowspan="2">Mix No</th><th colspan="2">Cement</th><th colspan="2">LSP</th><th rowspan="2">Water to Cement ratio</th><th colspan="3">Aggregate (Kg/m^3)</th><th rowspan="2">Water (Kg/m^3)</th><th rowspan="2">Vebe Time (S)</th></tr>
<tr><th>Kg/m^3</th><th>%</th><th>Kg/m^3</th><th>%</th><th>Coarse</th><th>Fine</th><th>Coarse to Fine ratio</th></tr>
<tr><td>A-12-SS</td><td rowspan="3">269</td><td rowspan="3">12</td><td colspan="2">-</td><td>0.40</td><td rowspan="3">1076</td><td rowspan="3">897</td><td rowspan="3">1.2</td><td rowspan="2">108</td><td>30</td></tr>
<tr><td>A-12-LFS</td><td colspan="2">-</td><td>0.40</td><td>32</td></tr>
<tr><td>A-12-LMS</td><td>118</td><td>6*</td><td>0.47</td><td>127</td><td>34</td></tr>
<tr><td>B-15-SS</td><td rowspan="3">332</td><td rowspan="3">15</td><td colspan="2">-</td><td>0.40</td><td rowspan="3">1028</td><td rowspan="3">857</td><td rowspan="3">1.2</td><td rowspan="2">133</td><td>26</td></tr>
<tr><td>B-15-LFS</td><td colspan="2">-</td><td>0.40</td><td>27</td></tr>
<tr><td>B-15-LMS</td><td>113</td><td>6*</td><td>0.43</td><td>143</td><td>29</td></tr>
</table>

* 6% LSP is added to RCCP mixture by weight of total aggregate

3.10.3 Research design for third objective

For all mixtures in the current study, 12% Portland cement by mass of total dry solids (268 Kg/m^3) was used. In order to investigate the effect of moisture content on the performance of RCCP, six mixtures were prepared at different water contents of 4.5%, 5%, 5.5%, 6%, 6.5% and 7%.

In order to determine the optimum moisture contents, samples were taken from the compacted specimens and dried in an oven at 105 ℃ till a constant mass. The water content, wet density and dry density were then calculated by using following equations:

$$w = \frac{w_{wet} - w_{dry}}{w_{dry}} \times 100 \qquad \text{(Eq.3.7)}$$

where *w* is water content (%); W_{wet} is weight of wet concrete (gr) and W_{dry} is dry weight (gr)

$$\gamma_{wet} = \frac{\text{weight of wet concrete (Kg)}}{\text{Volume of concrete (m}^3\text{)}} \qquad \text{(Eq.3.8)}$$

$$\gamma_{dry} = \frac{\gamma_{wet}}{(1 + w)} \qquad \text{(Eq.3.9)}$$

The relationship between water contents and dry density were plotted for all mixture which prepared according to the soil compaction concept and vibrating hammer method (ASTM C1435, 2008). From the both moisture-density curve, the optimum moisture content corresponding to the maximum dry density was determined, as shown in Figure 3.13 and Figure 3.14. As seen in the figures, the optimum moisture content is about 5.7%.

The mix proportions of all mixtures are summarized in Table 3.6. The freshly-mixed concretes were molded in cylindrical molds by using an electric vibrating hammer and

Modified proctor rammer. Electric vibrating hammer equipped with a shaft and circular plate according to ASTM C1435 (2008).

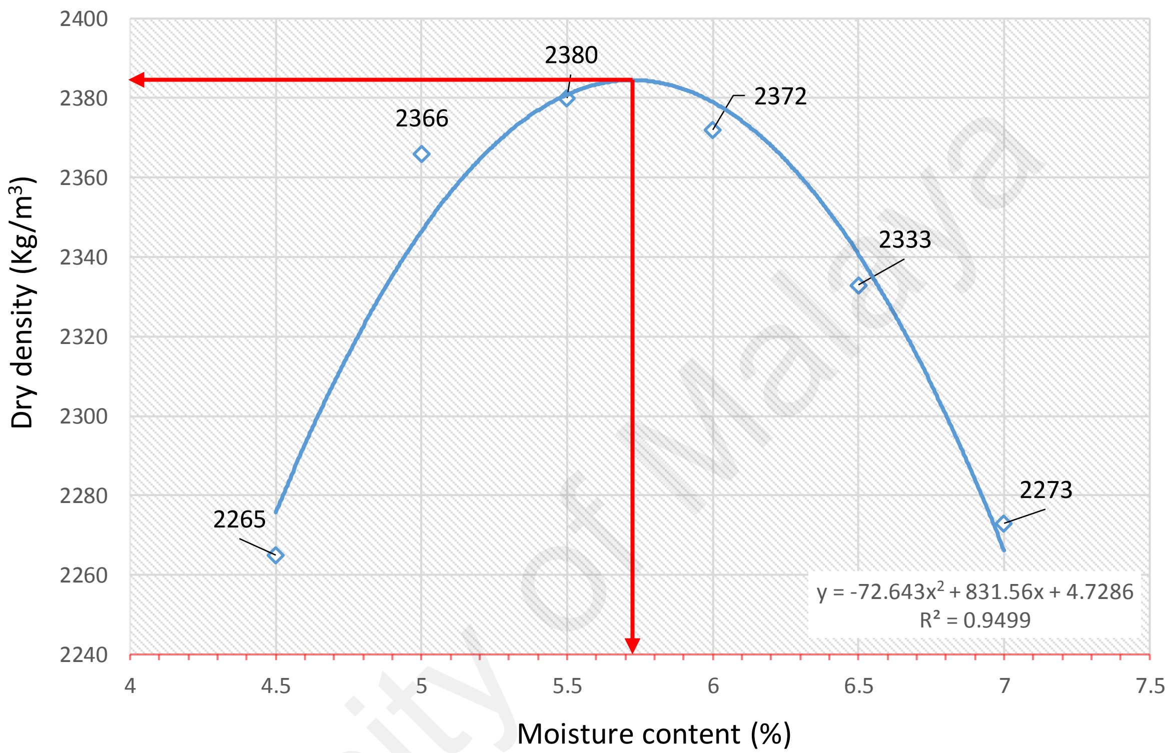


Figure 3.13: Relation between moisture content and dry density of RCCPs by modified proctor rammer

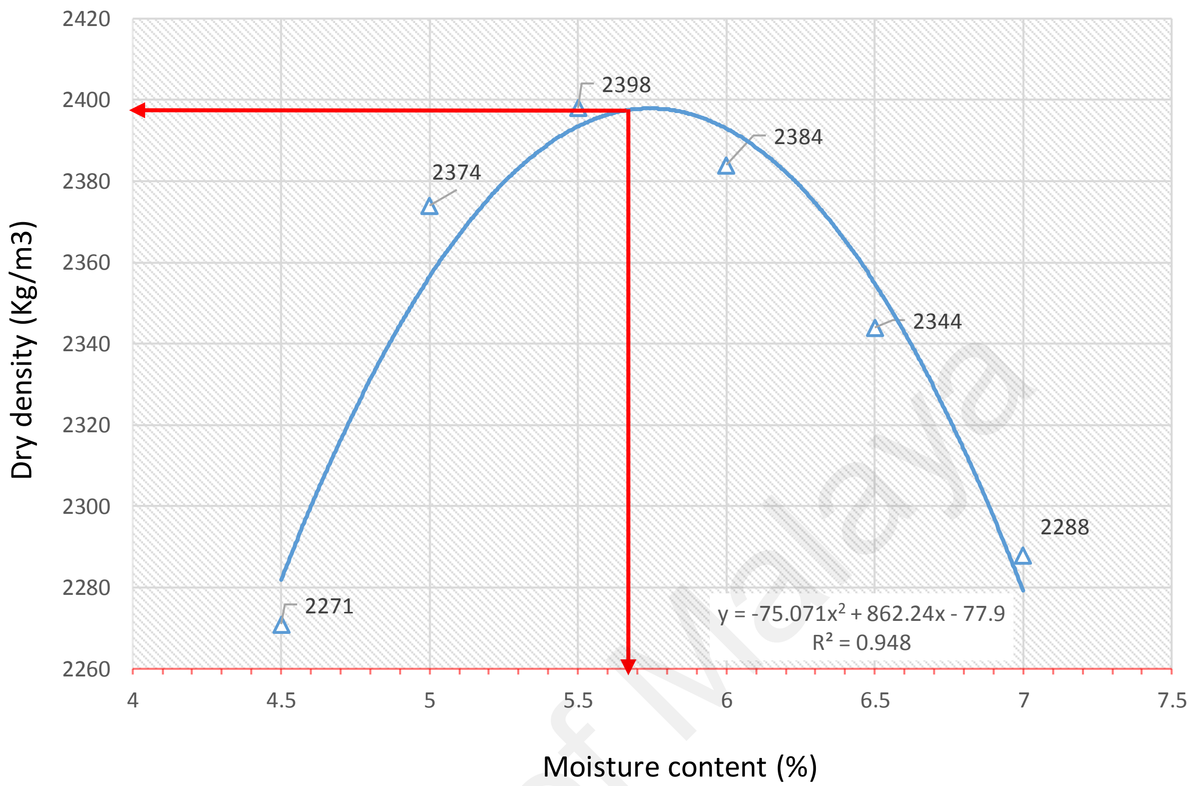


Figure 3.14: Relation between moisture content and dry density of RCCPs by electric vibrating hammer

Table 3.6: Mix proportion details

Mix No	Cement		Water (Kg/m³)	Water to Cement ratio	Moisture content (%)*	Coarse aggregate (Kg/m³)	Fine aggregate (Kg/m³)	Coarse to fine aggregate
	Kg/m³	%						
1			101	0.37	4.5	1081	901	
2			112	0.41	5	1075	895	
3	268	12	123	0.45	5.5	1069	891	1.2
4			134	0.49	6	1064	886	
5			146	0.54	6.5	1056	880	
6			157	0.58	7	1050	875	

* By mass of total dry solids

3.10.4 Research design for fourth objective

In this study, both RCCP and NVC contains 15% Portland cement (329 kg/m^3) by mass of total dry solids. The cementitious materials in RCCP is usually ranging from 250 to 350 kg/m^3 (Khayat & Libre 2014). With the same cement ratio, two RCCP mixtures with Fly ash (FA) and Ground-granulated blast-furnace slag (GGBFS) were made. Then, 1.5% of superplasticizer was added to RCCP to get NVC mixtures with suitable slump. The FA and GGBFS are widely used as a supplementary cementitious material (SCM) for pozzolanic reaction in concrete. The use of FA in RCCP is an effective solution to provide fine particles required for full density (Vahedifard et al., 2010). FA and GGBFS usually use by 25% and 30% of the total volume of cementitious material in RCCP, respectively (Harington et al., 2010). It was also found that the addition of GGBFS to RCCP led to reduced porosity, lower water absorption and permeability (Aghaeipour & Madhkhan, 2017). The mix proportions of all concretes are summarized in Table 3.7. In this table, "NVC1" and " NVC2" stand for normal vibrated concrete with FA and GGBFS, respectively. In addition, "RCCP1" and "RCCP2" stand for roller compacted concrete pavement with FA and GGBFS, respectively. The water to binder (w/b) ratio is set 0.42 for all mixtures. In different real projects for RCCP application such as "port of Tacoma; intermodal yard" and " Atlanta; RCCP Shoulder" binders are included 270 kg/m^3 cement and 60 kg/m^3 FA with w/b ratio 0.47 and 300 kg/m3 cement with w/b ratio 0.53, respectively (Harington et al., 2010). Also, Atis et al (2004) reported an RCCP containing 340 kg/m^3 cement and 60 kg/m^3 FA with w/b ratio 0.41 and 28-day compressive strength 63 MPa.

Table 3.7: Mix proportion details

Mix ID	Cement		FA		GGBFS		Water to cement ratio	Aggregate (Kg/m^3)		Water (Kg/m^3)	Super plasticizer (Kg/m^3)
	Kg/m^3	%	Kg/m^3	%	Kg/m^3	%		Coarse	Fine		
NVC1	329	15	50	15*	0		0.42	917	873	159	4.935**
NVC2	329	15	0		50	15*	0.42	917	873	159	4.935**
RCCP1	329	15	50	15*	0		0.42	917	873	159	0
RCCP2	329	15	0		50	15*	0.42	917	873	159	0

* 15% fly ash is added to RCCP mixture by weight of total cement
** 1.5% superplasticizer is added to RCCP mixtures by weight of total cement

3.10.5 Research design for fifth objective

In this study, two groups of RCCP were used, containing 12% and 15% Portland cement by mass of total dry solids (268 and 329 kg/m3), respectively. Then, 0.25% and 0.5% superplasticizer was added to RCCP mixtures at both cement content. It should be noted that the use of more than 0.5% superplasticizer resulted in normal-slump concrete. The mix proportions of all concretes are given in Table 3.8.

In this table, "A-12" and "B-15" stand for RCCPs containing 12% and 15% cement content, respectively. In addition, "A-12-0.25" and "B-15-0.25" stand for RCCPs with 12% and 15% cement content containing 0.25% superplasticizer by weight of total cement, respectively. Moreover, "A-12-0.5" and "B-15-0.5" stand for RCCPs with 12% and 15% cement content containing 0.5% superplasticizer by weight of total cement, respectively.

Table 3.8: Mix proportion details

<table>
<tr><th rowspan="3">Mix</th><th colspan="2" rowspan="2">Cement</th><th colspan="2" rowspan="2">FA</th><th colspan="3">Aggregate (Kg/m^3)</th><th rowspan="3">Water (Kg/m^3)</th><th rowspan="3">Water to Binder ratio</th><th colspan="2" rowspan="2">Super plasticizer</th></tr>
<tr><th rowspan="2">Coarse aggregate</th><th rowspan="2">Fine aggregate</th><th rowspan="2">Coarse to Fine ratio</th></tr>
<tr><th>Kg/m^3</th><th>%</th><th>Kg/m^3</th><th>%*</th><th>Kg/m^3</th><th>%*</th></tr>
<tr><td>A-12</td><td rowspan="3">268</td><td rowspan="3">12</td><td rowspan="3">40</td><td rowspan="3">15</td><td rowspan="6">917</td><td rowspan="6">873</td><td rowspan="6">1.05</td><td rowspan="3">130</td><td rowspan="3">0.42</td><td colspan="2">0</td></tr>
<tr><td>A-12-0.25</td><td>0.67</td><td>0.25</td></tr>
<tr><td>A-12-0.5</td><td>1.34</td><td>0.50</td></tr>
<tr><td>B-15</td><td rowspan="3">329</td><td rowspan="3">15</td><td rowspan="3">50</td><td rowspan="3">15</td><td rowspan="3">150</td><td rowspan="3">0.4</td><td colspan="2">0</td></tr>
<tr><td>B-15-0.25</td><td>0.81</td><td>0.25</td></tr>
<tr><td>B-15-0.5</td><td>1.62</td><td>0.50</td></tr>
</table>

*15% fly ash is added to RCCP mixture by weight of total cement
** Superplasticizer is added to RCCP mixtures by weight of total cement

3.10.6 Research design for sixth objective

Two groups of RCCPs containing 12% (268 kg/m^3) and 15% (329 kg/m^3) OPC by weight of total dry solids were used. The cementitious materials in RCCP is usually ranging from 250 to 350 kg/m^3 (Harrington et al., 2013; Khayat, & Libre, 2014). LECA was replaced by volume of coarse aggregate in varying percentages of 25, 50, 75 and 100% at both cement contents. In this way, first LECA were pre-immersed in the water for about 1 h before mixing, then the LECA were placed on a sieve for 30 min to dry off the water to reach saturated surface dry (SSD) condition.

The mix proportions of all concretes are summarized in Table 3.9. In this table, " A-12" and " B-15" stand for RCCP containing 12% and 15% cement with normal weight aggregate, respectively. In addition, "A-12-25" and "B-15-25" stand for RCCP containing 12% and 15% cement with 25% LECA as coarse aggregate, respectively. "A-12-100" and " B-15-100" stand for RCCP containing 12% and 15% cement with totally LECA which replaced with normal weight aggregate, respectively. The water to cement (w/c) ratio is set 0.40 for all mixtures.

Table 3.9: Mix proportion details, Vebe time and density results

Mix ID	Cement		LECA		Water to Cement ratio	Aggregate (Kg/m^3)			Water (Kg/m^3)	Vebe Time (S)	Oven dry density (Kg/m^3)
	Kg/m^3	%	Kg/m^3	%		Coarse	Fine	Coarse to Fine ratio			
A-12			0	0		1076				34	2381
A-12-25			154	25		807				33	2191
A-12-50	269	12	308	50		538	897		108	31	2021
A-12-75			462	75		269				29	1911
A-12-100			617	100		0				26	1794
B-15			0	0	0.40	1028		1.2		30	2398
B-15-25			147	25		771				28	2234
B-15-50	332	15	295	50		514	857		133	26	2087
B-15-75			442	75		257				23	1964
B-15-100			590	100		0				20	1855

The freshly-mixed concretes were compacted in cylindrical molds by electric vibrating hammer according to ASTM C 1435. The RCCP mixtures used in this study were designed based on the soil compaction concept in accordance with ASTM D1557. It should be noted that after heavy compaction with electric vibrating hammer, some of the cylindrical molds were opened and washed, mostly the LECA were in good condition and they were not broken. Figure 3.15 and Figure 3.16 shows the condition of LECA after compaction for RCCPs containing 25 and 100% LECA.

Figure 3.15: LECA condition after compaction for RCCP containing 25% LECA

Figure 3.16: LECA condition after compaction for RCCP containing 100% LECA

CHAPTER 4. RESULTS AND DISCUSSIONS

4.1 Introduction

In this chapter results and discussion of the current research are presented in six parts.

The first part entitled "The effect of coarse to fine aggregate ratio on the fresh and hardened properties of roller-compacted concrete pavement" specifies a suitable range of coarse to fine aggregate (C/F) ratio to attain a workable, high-strength and durable RCCP. This study investigates the effect of C/F ratio (0.6-1.8) on the fresh and hardened properties of two RCCPs with cement contents of 9% (204 kg/m^3) and 12% (268 kg/m^3).

In the second part entitled "The effect of using low fines content sand on the fresh and hardened properties of roller-compacted concrete pavement", the possibility of using low fines content sand in RCCP production was investigated. To study the effectiveness of using a sand which is out of the specified restriction on the properties of RCCP, three type of sands with different content of very fine particles (sand size finer than 75 micrometre) were used. The sands used are namely standard and limestone modified sands containing about 4.5% and a low fines content sand containing <1% very fine particles. Two types of RCCP containing 12% (269 kg/m3) and 15% (325 kg/m3) cement were used as control mix.

In the third part entitled " Optimum moisture content in roller-compacted concrete pavement", engineering properties of RCCP at different moisture contents of 4.5%, 5%, 5.5%, 6%, 6.5%, 7% and 12% cement were investigated. In this part the potential improvements in RCCP associated with the properties of fresh and hardened concrete at moisture content lower than optimum moisture content, which is corresponded to maximum dry density was studied.

The differences between RCCP and normal vibrated concrete in fresh and hardened states were assessed in the fourth part entitled "A comparison between roller-compacted concrete pavement and normal vibrated concrete". This part presents a comprehensive numerical comparison between normal vibrated concrete and RCCP.

In the fifth part entitled " The effect of superplasticizer on the fresh and hardened properties of roller-compacted concrete pavement", the effect of using different amount of superplasticizer (0.25% and 0.50%) on the fresh and hardened properties of two RCCPs with cement contents of 12% (269 kg/m3) and 15% (325 kg/m3) was investigated.

Finally, in the sixth part entitled "Engineering properties of roller-compacted lightweight concrete pavement" the effects of Lightweight Expanded Clay Aggregates (LECA) on the properties of RCCP was investigated. LECA was used to replace coarse aggregate with various dosages of 25, 50, 75 and 100% by volume. Two types of RCCP containing 12% (269 kg/m3) and 15% (332 kg/m3) cement were used as control mix.

4.2 The effect of coarse to fine aggregate ratio on the fresh and hardened properties of roller- compacted concrete pavement

4.2.1 Results and analysis

4.2.1.1 Vebe Time

The Vebe time for all RCCP mixes are presented in Table 3.3. According to the test results, the Vebe time increased with an increase in C/F ratio and decreased with an increase in cement content from 9% to 12%. Increasing the cement content in RCCP from 9% to 12% decreased the Vebe time by about 12%. In addition, increasing the C/F ratio in RCCP from 0.6 to 1.8 increased the Vebe time by up to three times. According to ACI 325, the Vebe time for producing RCCP is limited to 30-40 s, whereas Gauthier and Marchand (2005) concluded that the Vebe time for RCCP must be between 40 and 90 s. Vahedifard et al. (2010) studied the workability of non-air-entrained low-cement content RCCP mixtures. They reported that increasing the cement content in RCCP from 12% to 15% decreased the Vebe time by 10%.

Figures 4.1 - 4.6 illustrate the RCCP surface textures during the Vebe test for C/F ratios of 0.6, 1.2, 1.4 and 1.8, for both cement contents. As seen in these figures, all concretes were dry with zero slump. During this test, it was observed that both cement contents exhibited some segregation at C/F ratios of 0.6, 0.8 and 1.8. This could be because 1) using NMSA of 19 mm is not suitable for C/F ratios of 0.6 and 0.8; and 2) using C/F ratios above 1.6 is not acceptable, as higher ratios cannot provide a dense solid structure and well-graded aggregate in RCCP. However, based on visual observations of the compacted concrete during the Vebe test, the finished surfaces of RCCP mixtures with a C/F ratio of 1.2 exhibited the best condition.

Figure 4.1: Surface texture of A-9-1 RCCP in Vebe test

Figure 4.2: Surface texture of A-9-4 RCCP in Vebe test

Figure 4.3: Surface texture of A-9-7 RCCP in Vebe test

Figure 4.4: Surface texture of B-12-1 RCCP in Vebe test

Figure 4.5: Surface texture of B-12-4 RCCP in Vebe test

Figure 4.6: Surface texture of B-12-7 RCCP in Vebe test

4.2.1.2 Compressive strength

Based on ASTM C 330-89, the 28-day cylinder compressive strength should not be less than 17 MPa (Neville, 2008). PCA noted that the compressive strength of RCCP is comparable to that of conventional concrete and typically ranges from 28 to 41 MPa.

Figures 4.7- 4.9 display the relationships between compressive strength and C/F ratio for RCCPs containing 9% and 12% cement. One-day compressive strength indicates that increasing the C/F ratio for RCCP containing low cement (9%) had a significant effect when the C/F ratio was increased up to 1.4. For RCCP with 12% cement, increasing the C/F ratio up to 1.2 had no effect on compressive strength. The RCCP with 9% cement exhibited reduced compressive strength when the C/F ratio was more than 1.4 at early ages, whereas the RCCP with 12% cement showed an increment in compressive strength when the C/F ratio increased from 1.2 to 1.8.

The difference in behavior between the two RCCPs can be explained by the fact that increasing the C/F ratio reduces the bond length between coarse aggregates. For the same bond type, a shorter bond is stiffer than a longer bond. RCCP with 9% cement had weaker bonds compared to RCCP with 12% cement. Therefore, the shorter bond length in this concrete improved the strength up to a certain level at early ages. However, a further reduction in bond length could not improve the strength due to the excessive stress concentration in shorter, weaker bonds between coarse aggregates for 9% cement, which was not strong enough at early ages. The enhanced strength of RCCP with 9% cement and different C/F ratios signifies that when the bonds were very weak, i.e. at 1-day age, increasing the C/F ratio improved the strength up to the ratio of 1.4. Moreover, further hydrating the cement at 7 days did not affect the compressive strength for C/F ratios over 1.4. As cement hydration was complete at 28 days and due to the stronger bond compared to 1 and 7 days, there was no reduction in compressive strength. The early age and 28day compressive strength test results for RCCP with 12% cement prove that if the bond quality is high, the reduced bond length caused by increased C/F ratio can always improve the compressive strength of RCCP with time.

It should be noted that increasing the C/F ratio in conventional concrete usually results in water being trapped under large size aggregates. Aggregates with trapped water cause poor bonding between the aggregate and cement matrix. However, this cannot happen in RCCP because of the dense, well-graded aggregates and heavy compaction.

The compressive strength test results revealed that the impact of cement on compressive strength gain for low C/F ratios (below 1.0) was considerable. In addition, the positive effect of increasing the cement content at C/F ratios between 1 and 1.8 was more significant than the effect of increasing the C/F ratio at all ages. However, it is worth noting that the improvement in compressive strength due to the increase in cement content was more significant at C/F ratios in the 0.6-1.0 range. Increasing the cement content from 9% to 12% for C/F ratios of 0.6-1 and 1-1.8 increased the compressive strength by about 142% and 50% respectively, at 28 days. Based on the Vebe time and compressive strength test results, it can be concluded that the most suitable C/F ratio for RCCP is within 1-1.4.

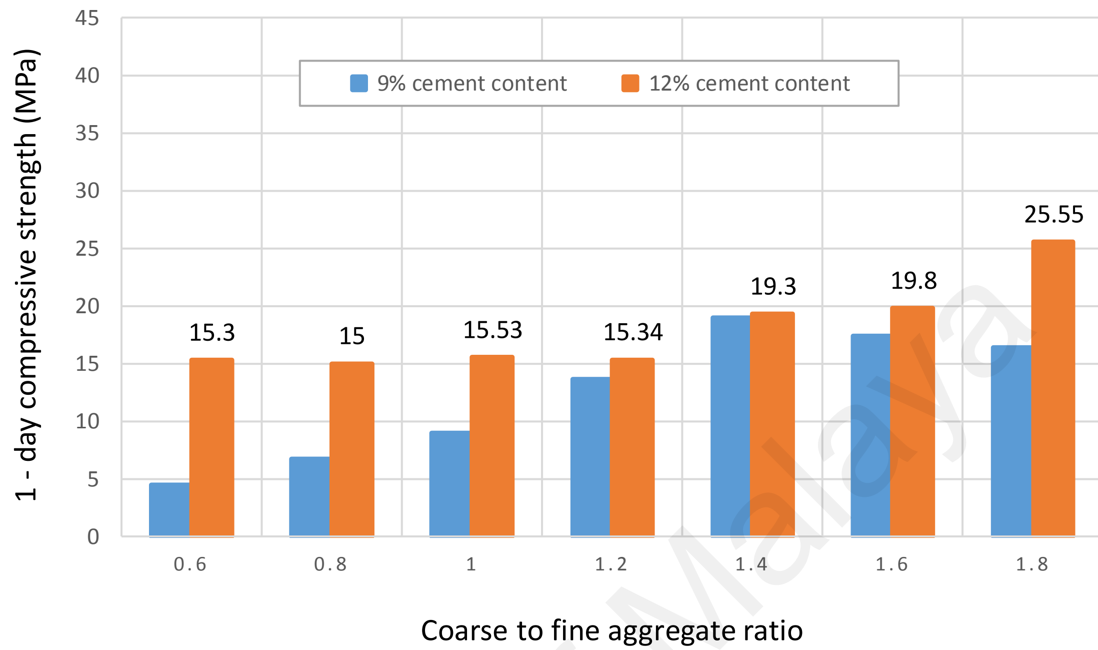


Figure 4.7: Relationship between coarse to fine aggregate ratio and 1- day compressive strength

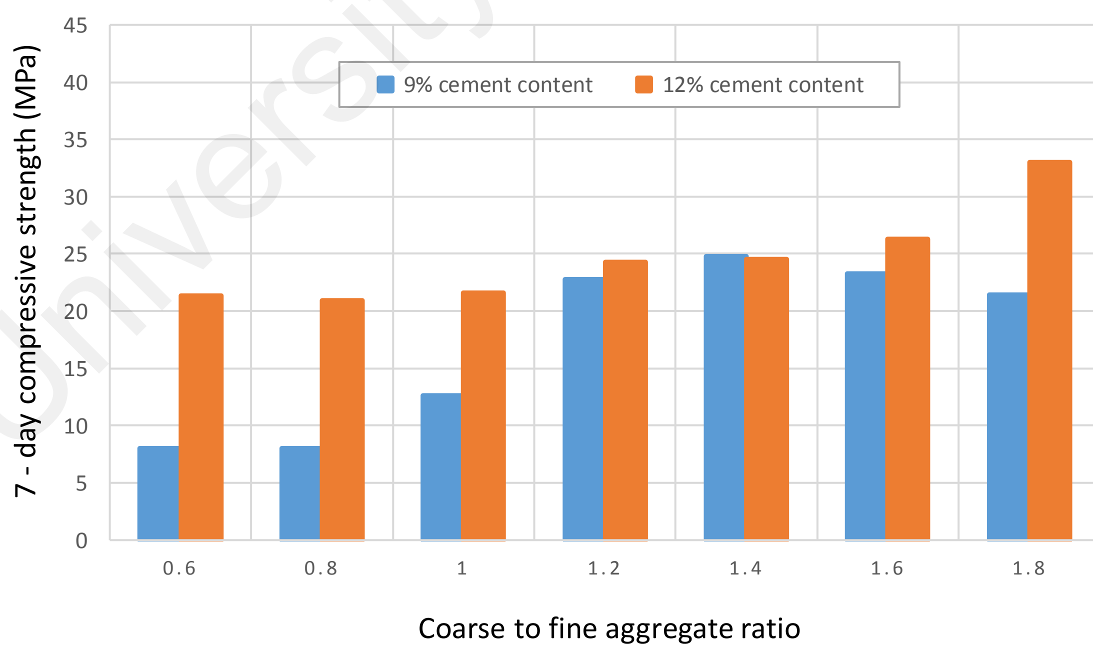


Figure 4.8: Relationship between coarse to fine aggregate ratio and 7- day compressive strength

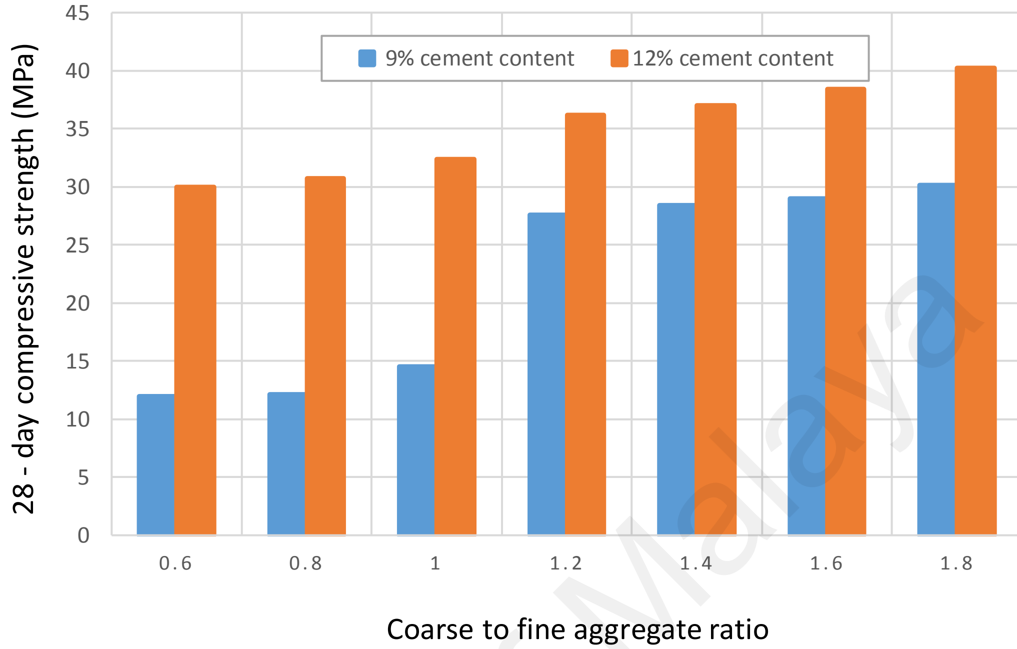


Figure 4.9: Relationship between coarse to fine aggregate ratio and 28 - day compressive strength

4.2.1.3 Tensile strength

Micro-cracking is highly determinative of the failure of concrete under tension associated particularly with the interfacial region between the hydrated cement paste and the aggregate particles (Mindess et al., 2002). The Interfacial Transition Zone (ITZ) has an essential effect on the properties of concrete, because it tends to act as the "weaker link in the chain" compared to the bulk cement paste and aggregate particles (Jennings & Thomas, 2009).

a. Splitting tensile strength

The splitting tensile strength was determined at 1, 7 and 28 days and the results are presented in Figures 4.10 - 4.12**.** The splitting tensile strengths of RCCP with 9% cement content at 1, 7 and 28 days were 1.34-2.25 MPa, 1.3-2.96 MPa and 1.56-3.71 MPa, respectively. For 12% cement content the splitting tensile strength was in the ranges of 2.58-3.04 MPa, 2.95-3.9 MPa and 4-4.9 MPa, respectively. Previous studies showed that depending on the RCCP mix design, the splitting tensile strength of RCCP can be between 2 and 4 MPa (Atiş et al., 2004; Chi & Huang, 2014; Atiş, 2005).

Generally, the effect of C/F ratio on the splitting tensile strength of RCCP is similar to the compressive strength trend. A significant improvement in splitting tensile strength was observed for RCCP containing 9% cement when the C/F ratio increased from 1.0 to 1.2. In RCCP with 9% cement content, increasing the C/F ratio from 1.6 to 1.8 reduced the splitting tensile strength by about 25% and 10% for 1 and 7day samples, respectively, and to about 0% at 28 days. The significant reduction in splitting tensile strength at early ages may be due to weak mortar and the stress concentration from the coarse aggregates. However, with the progressing cement hydration and consequently stronger mortar, the splitting tensile strength could be significantly improved at later ages. Therefore, when the cement content in RCCP is low and the C/F ratio is very high, e.g. 1.6-1.8, proper curing to continue cement hydration is essential. On the other hand, for 12% cement content, steady increase in tensile strength of around 18%, 32% and 22% was recorded when the C/F ratio increased from 0.6 to 1.8 at 1 day, 7 days and 28 days, respectively.

Increasing the cement content from 9% to 12% affected the splitting tensile strength in different patterns based on C/F ratios of 0.6-1, 1-1.2 and 1.2-1.8. When the C/F ratio was in the 0.6-1.0 range, the splitting tensile strength of RCCP with 9% and 12% cement content was notably different. Increasing the cement content from 9% to 12% increased the splitting tensile strength by about 85% at early ages. However, the improvement was more substantial (about 134%) at the age of 28 days. For 1.0-1.2 C/F ratios, the splitting tensile strength of RCCP with 9% cement was close to that of RCCP with 12% cement. For a C/F ratio over 1.2, there was no significant difference between the splitting tensile strengths of both RCCPs at 1 day, except for the C/F ratio of 1.8. However, the splitting tensile strengths of RCCPs with 12% cement were approximately 22% and 29% higher than RCCPs with 9% cement at the ages of 7 and 28 days, respectively. From these results, it can be concluded that when the C/F ratio is below 1, the cement content has a substantial impact on splitting tensile strength, while at high C/F ratios increasing the cement content does not contribute to strength gain greatly. Therefore, for economic purposes, it is recommended to use less cement in RCCP when the C/F ratio is between 1.2 and 1.8.

The British Department of Transport (1976) specified that a concrete to be used in road construction must have at least 1.8 MPa splitting tensile strength at 28 days. The current test results demonstrate that all RCCPs except A-9-1 and A-9-2 satisfy this requirement.

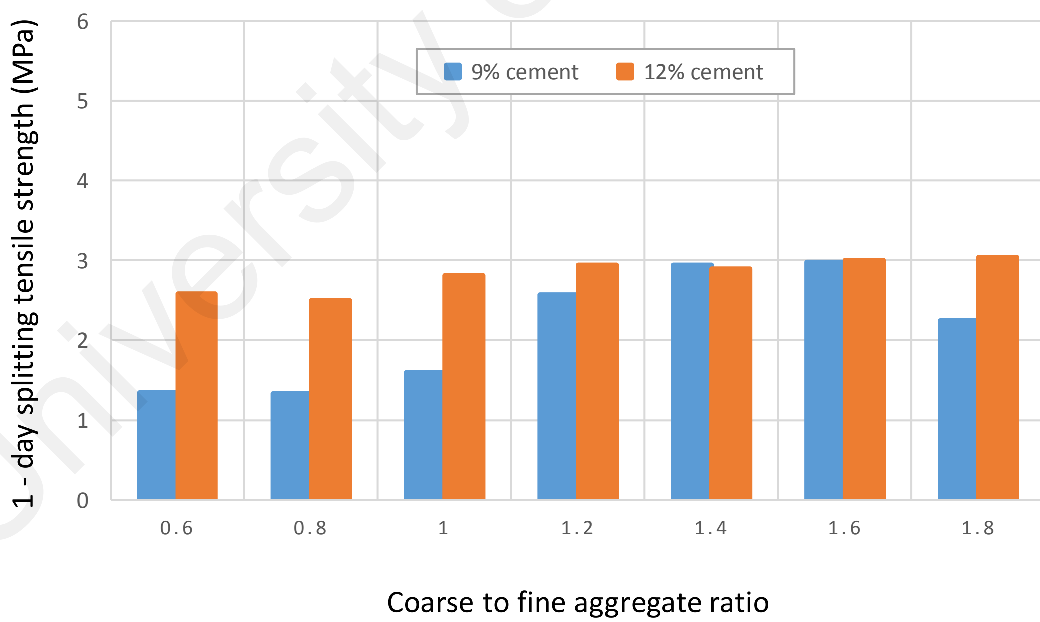


Figure 4.10: Relationship between coarse to fine aggregate ratio and 1- day Splitting tensile strength

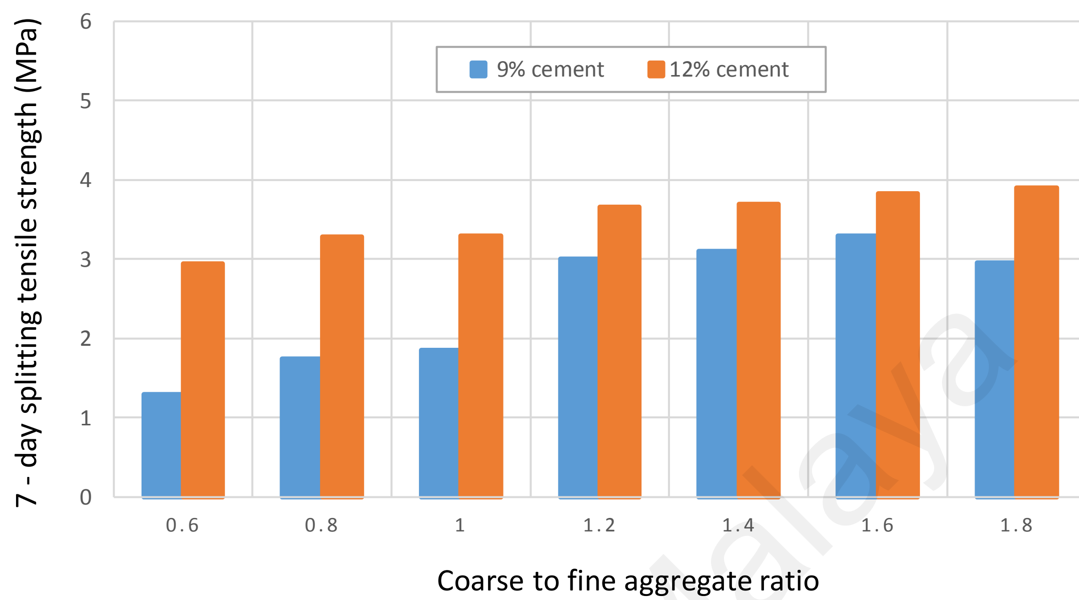


Figure 4.11: Relationship between coarse to fine aggregate ratio and 7- day Splitting tensile strength

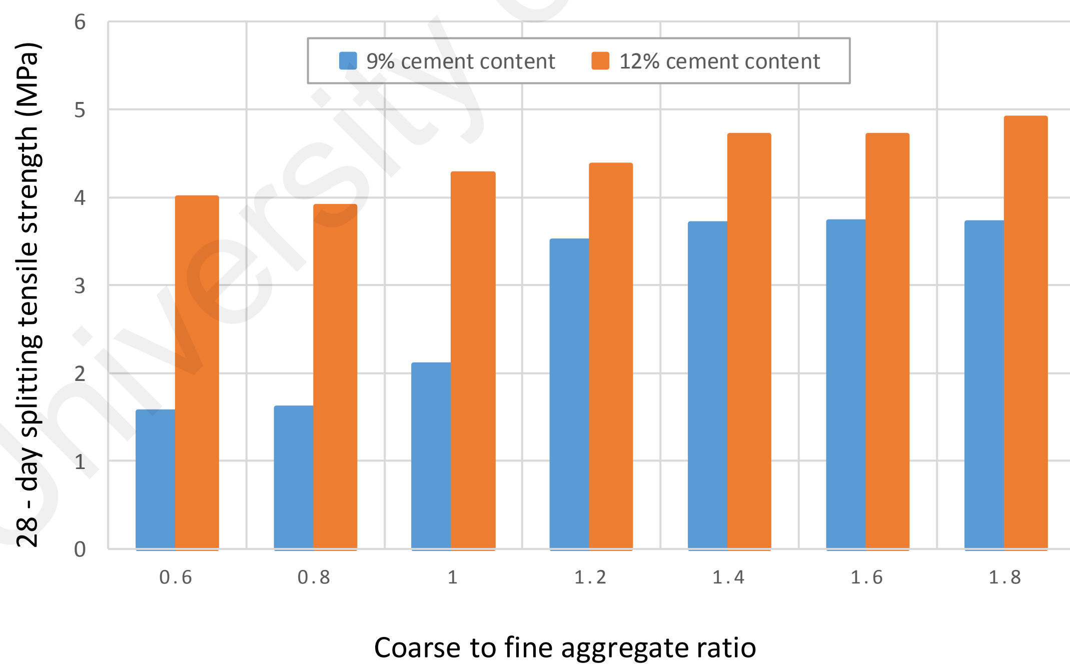


Figure 4.12: Relationship between coarse to fine aggregate ratio and 28 - day Splitting tensile strength

b. Flexural tensile strength

The flexural tensile strengths of the RCCPs produced are presented in Figures 4.13 - 4.15. The flexural tensile strength of RCCP with 9% cement content increased by about 25% and 142% at 1 day, 42% and 118% at 7 days, and 46% and 66% at 28 days for 0.6-1 and 1-1.2 C/F ratios, respectively. In addition, increasing the C/F ratio from 1.2 to 1.8 did not affect the flexural tensile strength considerably at any age. This means that for RCCP with 9% cement content, the effect of C/F ratios of 0.6-1, 1-1.2 and 1.2-18 is high, very high and not high respectively, on flexural tensile strength at any age.

For 12% cement content RCCP, the flexural tensile strength reached peaks of 3.2 and 4.06 MPa with a C/F ratio of 1.2 at 1 and 7 days, respectively. However, the flexural tensile strength at 28 days increased continually from 4.1 to 5.9 for C/F ratios of 0.6 to 1.8. It can be concluded that upon curing completion at 28 days, increasing the C/F ratio (by 1.2) significantly affected the flexural strength of RCCP with 9% cement, while at 12% cement content the flexural tensile strength increased steadily for 0.6 to 1.8 C/F ratios.

On the other hand, increasing the cement content from 9% to 12% developed the flexural tensile strength by 212% and 66% on average at 1 day, by 200% and 59% at 7 days and by 130% and 50% at 28 days for C/F ratios of 0.6-1 and 1-18, respectively. This indicates that cement greatly influences C/F ratios below 1, and it has a much lower influence on C/F ratios above 1.

The British Airport Authority (BAA) (1977) limits the flexural tensile strength to 4 MPa at 28 days. Thus, A-9-5, A-9-6 and all RCCPs with 12% cement content can be used as airport pavement. It should be noted that depending on the mix design, the flexural strength of RCCP is generally high, from 3.5 to 7 MPa (Harrington et al., 2010). In this study, the flexural tensile strength of RCCPs with 9% and 12% cement contents changed from 1.6 to 3.81 MPa and from 4.1 to 5.9 MPa for C/F rations of 0.6 to 1.8, respectively.

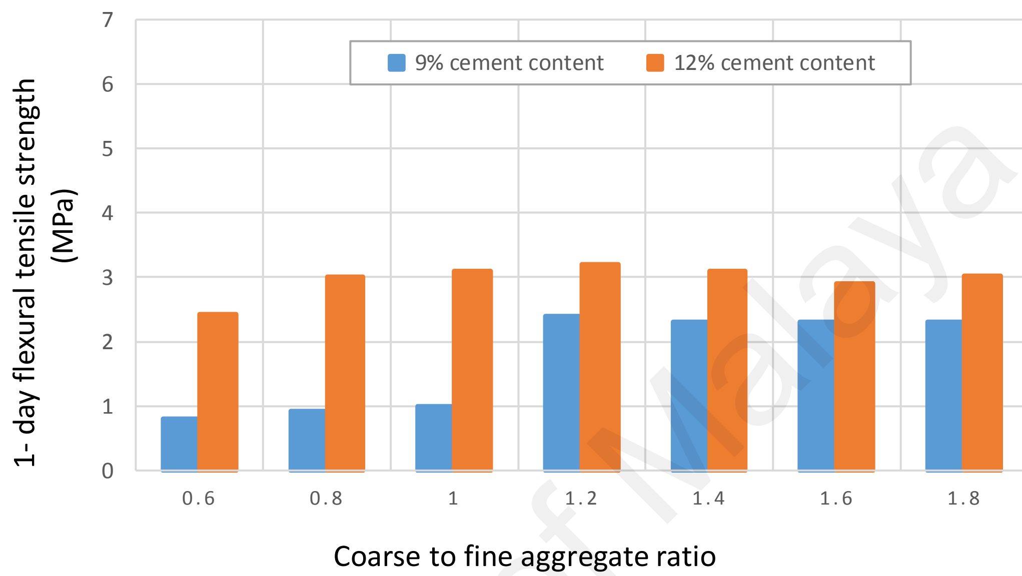


Figure 4.13: Relationship between coarse to fine aggregate ratio and 1- day Flexural tensile strength

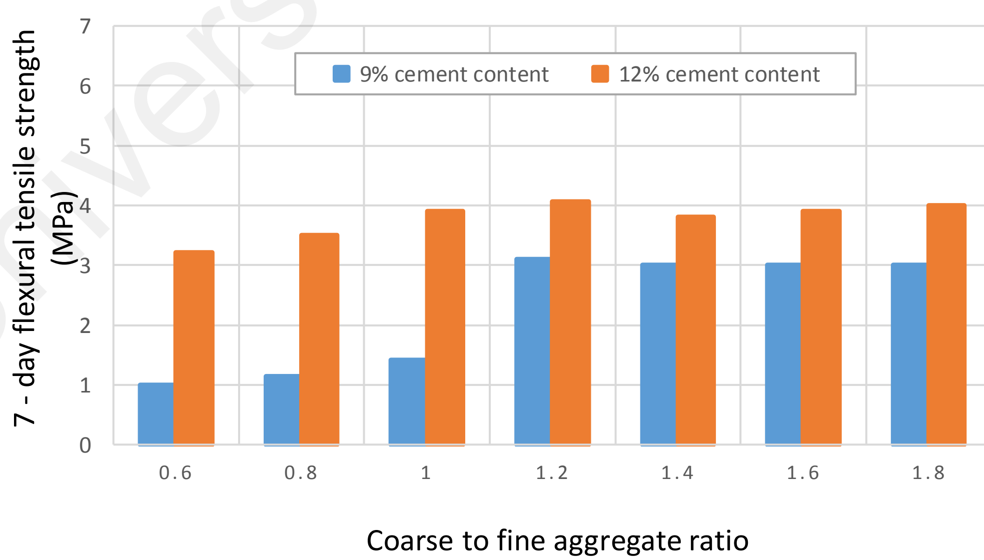


Figure 4.14: Relationship between coarse to fine aggregate ratio and 7 - day Flexural tensile strength

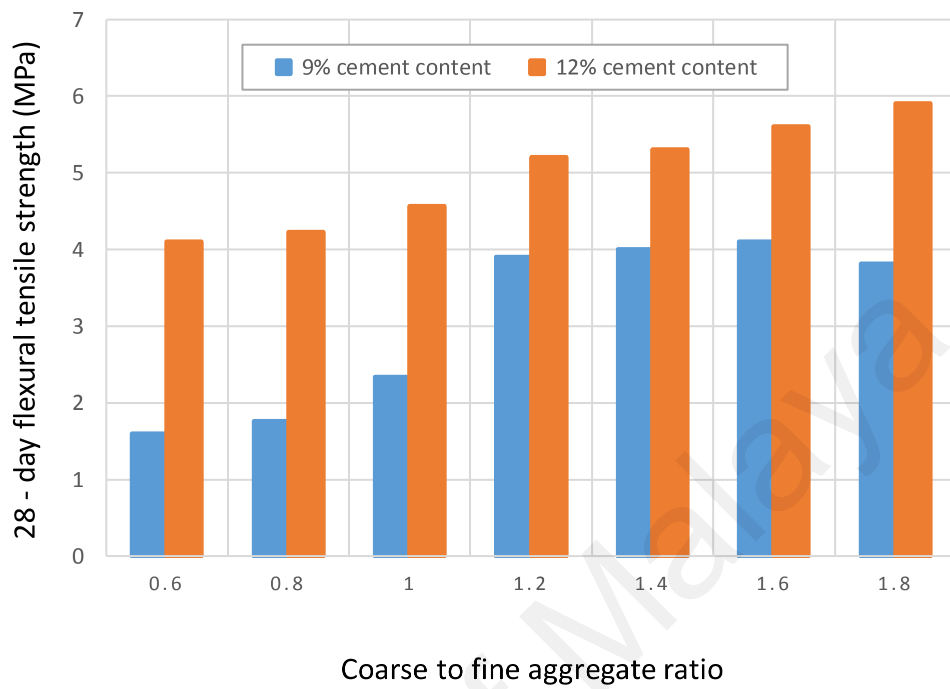


Figure 4.15: Relationship between coarse to fine aggregate ratio and 28 - day Flexural tensile strength

c. Flexural-to-splitting tensile strength ratio

Typically, the splitting tensile and flexural strengths of concrete are about 10% and 15% of the compressive strength, respectively (Li, 2004). RCCP has about the same ratio of compressive to tensile strength as normal concrete, ranging from 7 to 13%. The ratio depends on the strength level, age, aggregate type, and cement content (Mehta, 1986). In this investigation, the RCCP splitting tensile strength was 13.2% of the compressive strength. In addition, the RCCP flexural tensile strength was 14.2% of the compressive strength. This shows that the splitting tensile strength of RCCP was relatively high compared to conventional concrete.

In the present study, the average flexural to splitting tensile strength ratio obtained for RCCP was 1.05. However, ACI recommends this ratio should range from 1.4 to 1.6. Figure 4.16 represents the strong correlation between flexural tensile strength and splitting tensile strength.

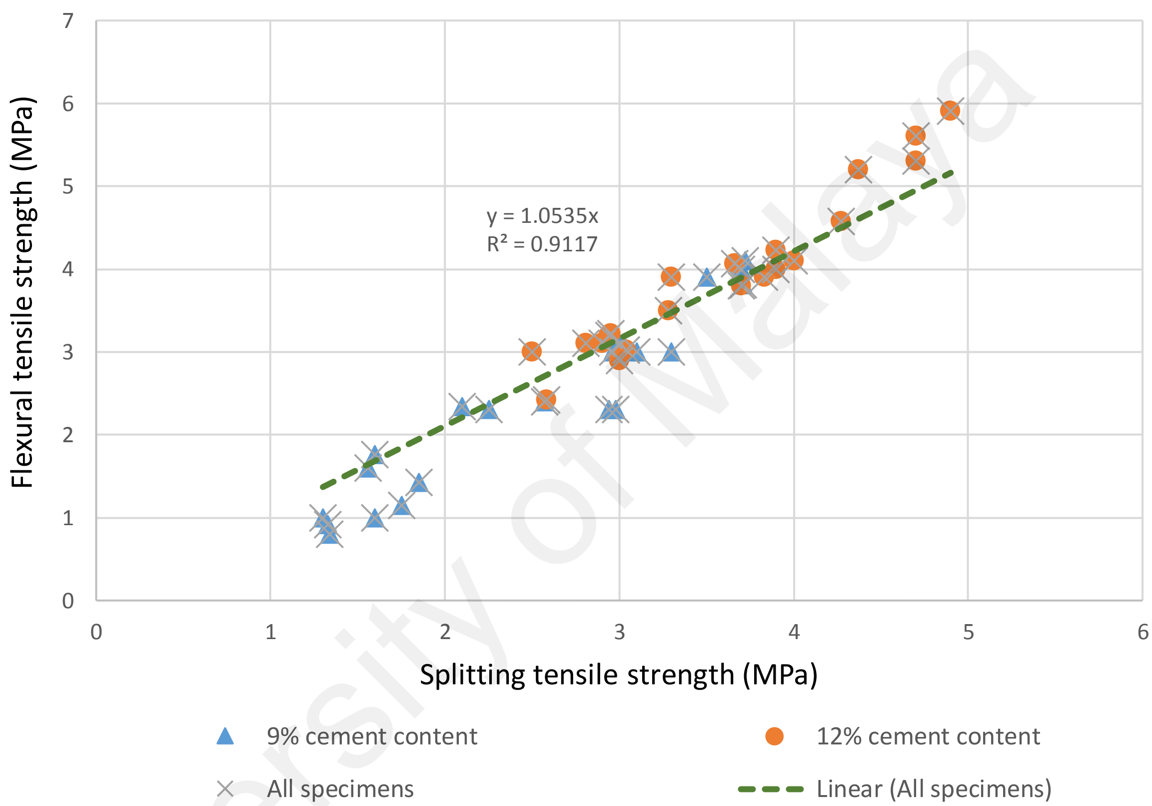


Figure 4.16: Relationship between flexural tensile strength and splitting tensile strength for 9% and 12% cement content RCCP

4.2.1.4 Porosity

Porosity is one of the most influential parameters on RCCP strength. Figure 4.17 presents the porosity of RCCPs containing 9% and 12% cement for different C/F ratios at 28 days. According to the test results, at 9% cement content the porosity decreased to about 60% when the C/F ratio increased from 0.6 to 1.2. However, the porosity slightly increased (by about 7%) as the C/F ratio increased from 1.2 to 1.8. The lowest porosity for RCCP with 9% cement occurred at C/F ratio of 1.2, and it was almost constant for C/F ratios above 1.2.

In contrast, the porosity of RCCP with 12% cement content decreased steadily from 4.45 to 2.62% with increasing C/F ratio from 0.6 to 1.8, respectively. In other words, the porosity at 12% cement content decreased by about 41% as the C/F ratio increased from 0.6 to 1.8. The most significant reduction was observed at C/F ratio of 1.0, and it was almost constant when the C/F ratio was more than 1.0.

Figure 4.17 clearly shows that increasing the cement content from 9% to 12% for C/F ratios of 0.6-1.2 and 1.2-1.8 reduced the RCCP porosity by 37% and 17% on average, respectively. Thus, the impact of cement on 1.2 C/F was considerable, but it was negligible for C/F of 1.2-1.8.

RCCP with lower porosity results in durable concrete with high compressive strength. However, excess porosity allows the penetration of air, water, and aggressive ingredients, thus reducing the durability of concrete in harsh environments (Khayat & Libre, 2014). Figure 4.18 illustrates a good correlation between porosity and compressive strength for RCCPs containing 9% and 12% cement. Evidently, the porosity of RCCP with 9% cement slightly increased from 3.17 to 3.41 and the compressive strength increased from 27.6 to 30.11 MPa. Then with increasing porosity from 3.41 to 5.17 the compressive strength decreased sharply from 30.11 to 14.5 MPa. Afterward, increasing the porosity from 5.17 to 6.21 decreased the compressive strength to 12.1 MPa. Finally, with increasing porosity from 6.21 to 7.85, the compressive strength remained constant. Conversely, for RCCP with 12% cement the porosity increased from 2.62 to 4.45 and consequently, the compressive strength decreased from 40.2 to 30MPa.

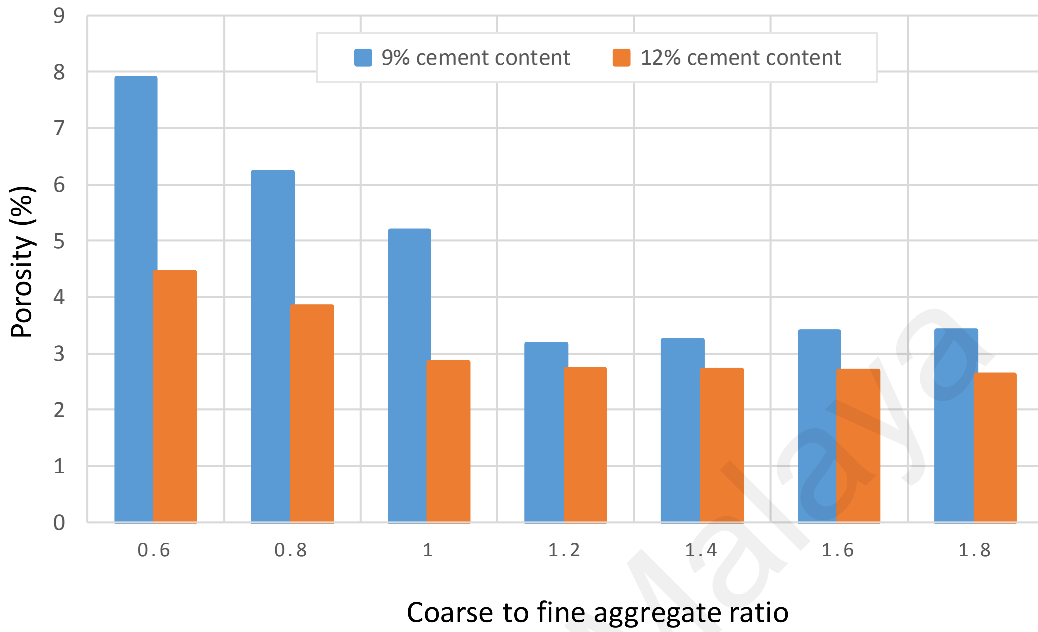


Figure 4.17: Relationship between porosity and C/F ratio of RCCP at 28 – day age

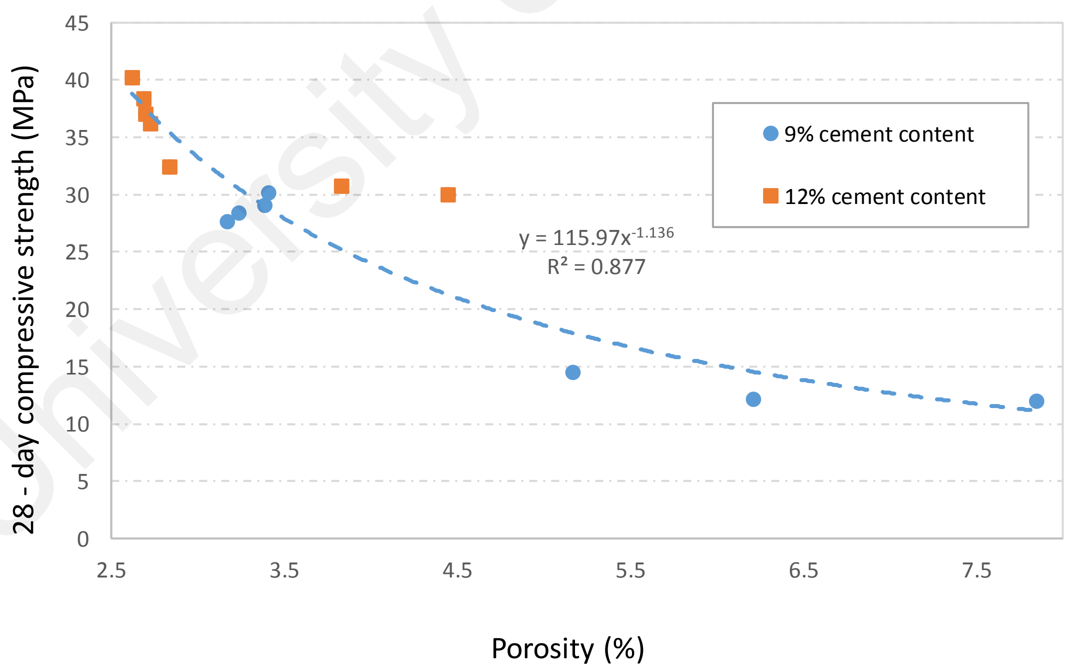


Figure 4.18: Relationship between 28 - day compressive strength and porosity for 9% and 12% cement content RCCP

4.2.1.5 Cold joint phenomenon

A cold joint is a weakness or discontinuity that occurs when a batch of concrete hardens before the next batch is placed on it. Delayed concreting results in cold joints, which can reduce concrete strength with minor to major impact (Rathi & Kolase, 2013). Also, multiple horizontal lifts must be placed in RCCP within an hour to ensure good bonding, unless a cold joint is planned (Harrington et al., 2010).

In this study, for 9% cement content, cold joints were observed in RCCPs with C/F between 0.6 and 1.0. No cold joint was observed in any RCCP specimens containing 12% cement. Therefore, to avoid cold joints in RCCPs containing low cement (9%), the ratio should be more than 1.0, otherwise the operation may be high-risk. Figure 4.19 shows a cold joint in a cylindrical specimen.

Figure 4.19: A cold joint in a cylindrical specimen for RCCP with 9% cement and C/F ratio of 0.6

4.3 The effect of using low fines content sand on the fresh and hardened properties of roller-compacted concrete pavement

4.3.1 Results and analysis

4.3.1.1 Vebe Time

Table 3.5 shows the vebe time for RCCPs. Based on the visual observation during mixing, placing and compaction; there was no segregation for all mixes. In addition, sufficient workability for all mixes was observed. As can be seen in Figure 4.20 and Figure 4.21, RCCPs with standard sand and modified sand had a tight texture surface in comparison with RCCPs containing low fines content sand. This is due to the lack on very fine aggregate (aggregate passing though the sieve #100 and #200). Kosmatka et al. (2011) reported that the amounts of fine aggregate passing sieve #50 and #100 affect workability, surface texture, air content, and bleeding of concrete. Aggregate properties including nominal maximum size of aggregate, fine aggregate content, and the amount of aggregate finer than the 75 µm passing sieve #200 affect workability of RCC in fresh state (Khayat & Libre 2014). Figure 4.21 shows the RCCP surface texture at the time of Vebe test for standard, low fines content and modified sands at 12% and 15% cement contents.

The Vebe time for RCCPs containing 12% and 15% cement was in the range of 30-34 sec and 26-29 sec, respectively. Based on ACI 325, Vebe time for RCCP has been limited to 30-40 s, while Gauthier and Marchand (2005) concluded that Vebe time for RCCP should be between 40 and 90 seconds. The results showed that increasing cement from 12% to 15% for RCCPs containing standard sand, low fines content sand and modified sand decreased Vebe time by 13.3%, 15.62% and 14.70%, respectively. It shows in the absence of sufficient very fine particles passing from sieve #100 and #200, the role of cement to decrease Vebe time is important. The workability of RCCP is most affected by the paste portion of RCCP mixture (ACI 207.5R-99).

Less paste in the mixture reduces the workability of RCCP and may increase the risk of segregation (Khayat & Libre, 2014). Vahedifard et al. (2010) studied the workability of non-air-entrained low-cement content RCCP mixtures. They reported that increasing cement content in RCCP from 12% to 15% can decrease Vebe time by 10 percent.

On the other hand, RCCPs containing low fines content sand and modified sand increased Vebe time by 6.6%, 13.3%, respectively, in comparison with RCCP with standard sand at 12% cement content. Also, for RCCPs with 15% cement containing low fines content sand and modified sand increased Vebe time by 3.8%, 11.5%, respectively. It shows that the significant increases of Vebe time due to addition of 6% LSP.

Figure 4.20: Surface texture in slump test. a: A-12-SS; b: A-12-LFS; c: A-12-LMS; d: B-15-SS; e: B-15-LFS; f: B-15-LMS

Figure 4.21: Surface texture in Vebe time test. a: A-12-SS; b: A-12-LFS; c: A-12-LMS; d: B-15-SS; e: B-15-LFS; f: B-15-LMS

4.3.1.2 Compressive strength

Figure 4.22 shows the compressive strength results of RCCP mixes containing different types of sand and cement content at different ages. As can be seen, RCCPs containing 12% cement with standard sand and low fines content sand have the approximately same compressive strength of 21 MPa and 29 MPa at 1 and 7days, respectively. However, slight reduction of about 3% was observed in RCCP mix with low fines content sand at 28-day. The same behavior was observed in RCCPs with 15% cement content. In 15% cement content, the compressive strength of RCCPs containing standard and low fines content sands were comparable at early ages of 1 and 7 days, while the use of low fines content sand caused 4% reduction on the 28-day compressive strength. These results show that the use of low fines content sand in RCCP, does not affect the compressive strength. In addition, the results revealed that without the specified percent sand passing from sieve #100 and #200, the suitable packing density can be obtained due to heavy compaction that must be applied for RCCP placement. In other words, the fine voids which is due to a lack of sand passing from sieve #100 and #200 could be removed largely because of heavy compaction in RCCP placement.

RCCPs containing modified sand with LSP showed the lowest compressive strength at all ages compared to RCCPs containing standard and low fines content sands. Although, by adding LSP to low fines content sand the gradation of sand was modified and the sand's curve was in the standard range, however, the compressive strength for RCCP containing this sand significantly reduced at all ages. The reduction on the compressive strength for RCCP with modified sand decreased about 27%, 28% and 28% for 12% cement and 27%, 21% and 18% for 15% cement at 1,7 and 28 day ages, respectively, in comparison with RCCPs containing standard sand.

The reduction of the compressive strength was due to higher mixing water in RCCP containing LSP. RCCPs containing 12% and 15% cement required 18% and 8% more water, respectively, to achieve a compactable fresh RCCP when LSP incorporated in the concrete mixture. As can be seen in these results, RCCP containing 15% cement needs less addition water, and, therefore, reduction of the compressive strength at 7 and 28-day ages was less than RCCP containing 12% cement. It can be concluded that RCCP is a kind of concrete which its compressive strength is highly affected with mixing water.

Increasing the cement content from 12% to 15% significantly improved the compressive strength of RCCP with modified sand at 7 and 28 days. Increasing the 1, 7 and 28-day compressive strength for this RCCP was about 5%, 19% and 26%, respectively. While, the increment for RCCPs with standard sand and low fines content sands was almost the same of 5%, 10% and 11%, respectively. These results show that when a material with high surface area (LSP in this study) is used in RCCP mixture, increasing the cement content is necessary to improve its rheological properties of fresh state and compensate reduction of the compressive strength at the service time. However, based on test results of compressive strength the use of LSP to modify low fines content sand is not necessary.

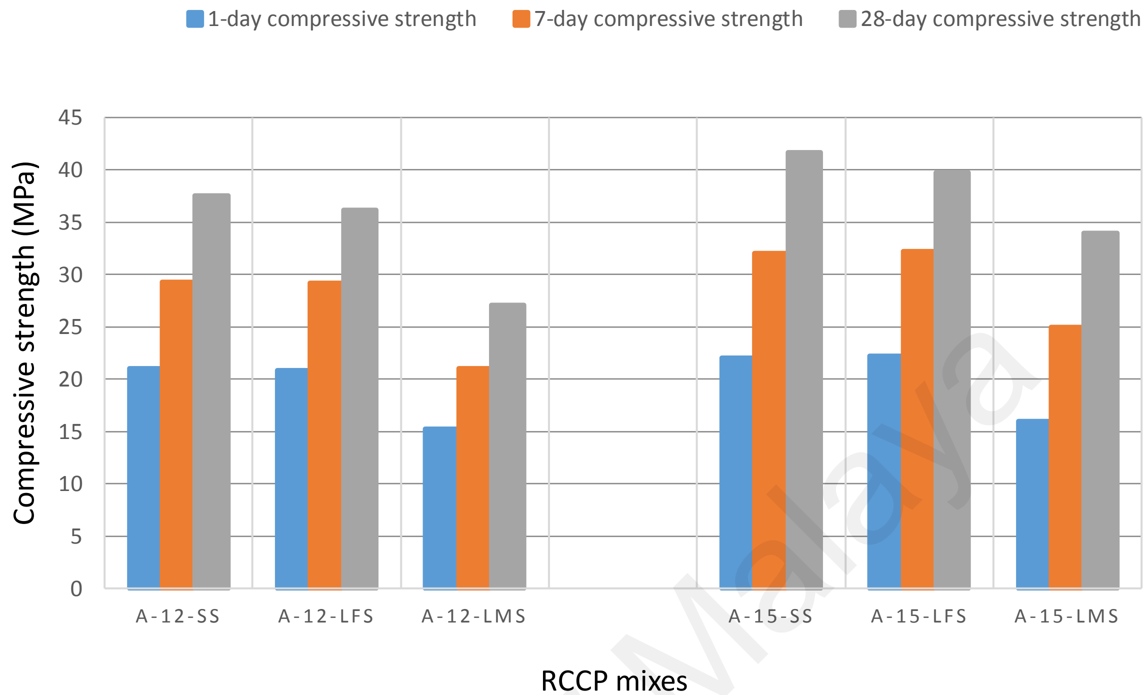


Figure 4.22: Compressive strength for RCCPs containing 12% and 15% cement

4.3.1.3 Splitting tensile strength

Test results of splitting tensile strength of all RCCPs at the ages of 1, 7 and 28 days are shown in Figure 4.23. Test results show that the splitting tensile strength of two RCCPs containing standard sand and low fines content sand are almost the same at all ages in both cement contents. This show that existing very fine particles (sands passing through sieve #100 and #200) in the sand used in RCCP is not critical.

Although, LSP modified the grading of low fines content sand, however, there was a considerable reduction of splitting tensile strength for both groups of RCCPs at all ages. The splitting tensile strength decreased about 29%, 25% and 23% for RCCP with 12% cement and 23%, 16%, 15% for RCCP with 15% cement at 1, 7 and 28 days, respectively, in comparison with RCCP containing standard-sand. It shows that the splitting tensile strength decline has been decreased slightly with further cement hydration by 28-day curing ages. So, completion of cement hydration for RCCP containing LSP can provide stronger structure.

On the other hand, increasing cement from 12% to 15% increased splitting tensile strength at all ages. Increasing cement from 12% to 15% for RCCPs containing standard sand, low fines content sand and modified sand raised the splitting tensile strength about 7%, 10% and 19% at 28 days, respectively. As same as compressive strength, the cement increment was more useful for RCCP with modified sand. In addition, increasing cement from 12% to 15% raised the splitting tensile strength of RCCP with low fines content sand more than RCCP containing standard sand. This may be due to exception of sufficient fine particles passing the sieve #100 and #200 in RCCP with low fines content sand.

The minimum splitting tensile strength of 1.85 MPa for concrete which is used in road construction is determined by British Department of Transport (1976). Thus, all RCCPs containing standard-sand, low fines content sand and modified sand could be used for road construction.

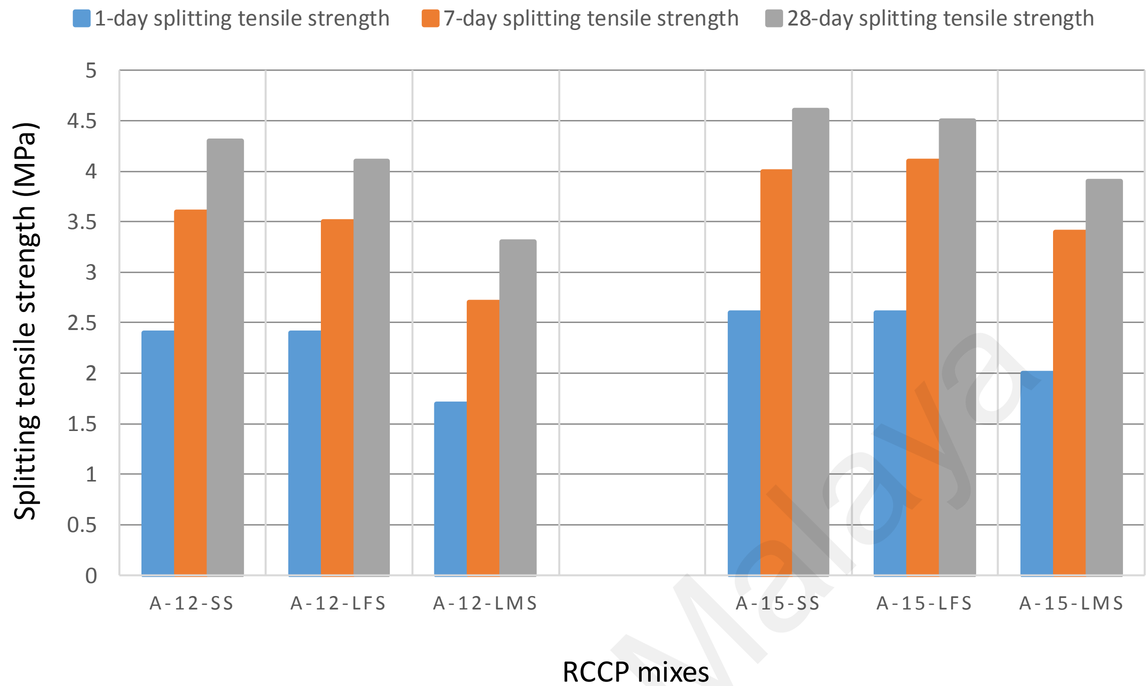


Figure 4.23: Splitting tensile strength for RCCPs containing 12% and 15% cement

4.3.1.4 Flexural tensile strength

The pavement usually is designed on the basis of flexural tensile strength (Delatte, 2014). However, opening the pavement to traffic may be on the basis of compressive strength. The flexural tensile strength results are shown in Figure 4.24. The flexural tensile strength results for RCCPs with 12% cement containing standard sand and low fines content sand was comparable at all ages. Also the same behavior was seen for RCCPs with 15% cement content. It means that the low fines content sand does not have negative effect on flexural tensile strength at all ages. However, there was a significant reduction for flexural tensile strength of RCCPs containing modified sand at all ages. The increase in mechanical properties (i.e., compressive and flexural strength) is generally commensurate with reduction in the water-to-cement ratio (Mehta, 1986). The flexural tensile strength for RCCPs with 12% and 15% cement containing modified sand decreased about 38% and

27% at 1 day, 35% and 13% at 7 days, 31% and 11% at 28 days, respectively. It shows that the reduction for flexural tensile strength of RCCPs with 15% cement containing modified sand was lower than RCCPs containing 12% cement at all ages.

Increasing cement from 12% to 15% increased also the flexural tensile strength of RCCPs at all ages. The highest increase for flexural tensile strength due to cement increment for RCCPs containing standard sand, low fines content sand and modified sand was observed at 7 days about 14%, 17% and 51%, respectively. However, it was not significant at 28-day curing ages for RCCPs containing standard and low fines content sands; in average of 8%. It should be noted that the role of cement increment was more considerable for RCCPs included limestone modified sand at all ages. Also, increasing cement from 12% to 15% was more useful for low fines content sand in comparison with standard sand.

A minimum allowable flexural strength of 4.13 MPa at 28 days for airport pavements is determined by Federal Aviation Administration (FAA) (2000). Also, the flexural strength of 4.0 MPa at 28 days is restricted by British Airport Authority (BAA) (1977). Thus, all RCCPs except A-12-3 can be used for airport pavements. In addition, the American Concrete Pavement Association (ACPA) specified a minimum flexural strength of 3.0 MPa or a compressive strength of 17 MPa for intersections. So, RCCPs in this study, containing standard sand and low fines content sand can be opened to traffic after 24 h.

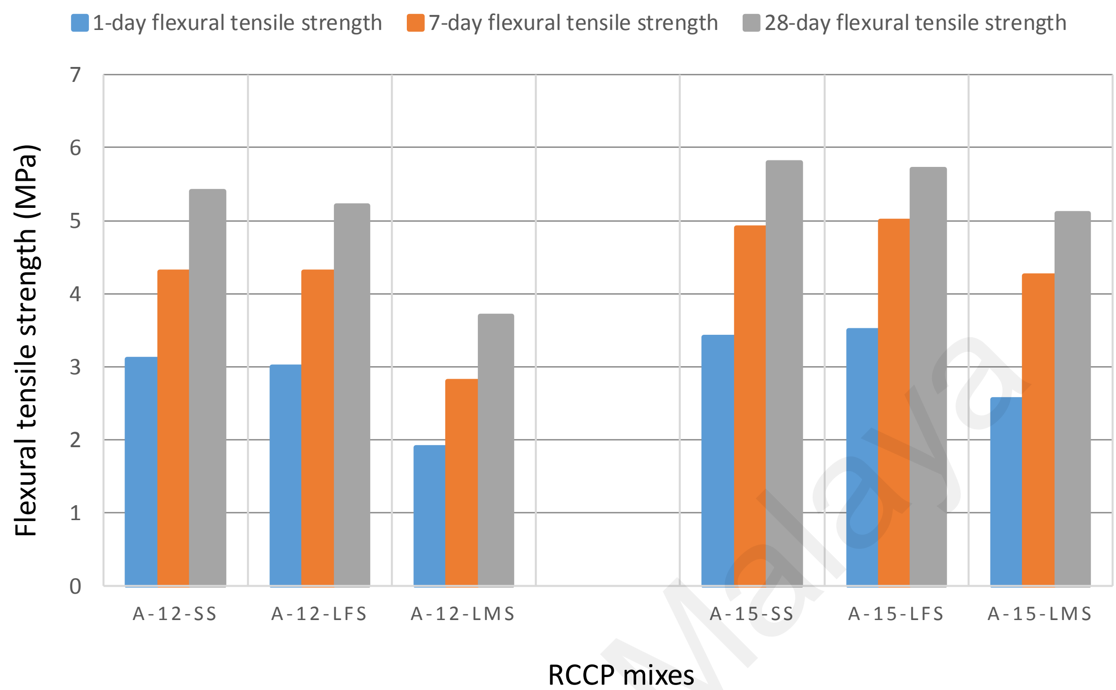


Figure 4.24: Flexural tensile strength for RCCPs containing 12% and 15% cement

4.3.1.5 Water absorption

Water absorption of concrete is fluid flow in porosities of unsaturated concrete specimens when there is not any external pressure on the specimens (Mohammadi, 2013). Water absorption usually uses as an important factor for quantifying the durability of cementitious systems (Castro et al., 2011). Previous studies indicate that the water absorption values are reduced with increase in the curing time, increase in the degree of consolidation, and decrease in the water-to-cement ratio (Mehta,1986). Comité euro-international du béton (CEB, 1989;192:83–5) divided concrete into good concrete with water absorption < 3%, average with water absorption 3-5% and poor concrete with water absorption > 5%.

The results for initial water absorption after 30 min and final water absorption after 72 h are demonstrated in Figure 4.25. As can be seen the initial surface water absorption of all RCCPs showed values lower than 3%, except A-12-LMS that indicated 4.5%. In addition, the final water absorption for RCCPs with 12% and 15% cement containing standard sand and low fines content sand was lower than 3%. However, it was 4.9% and 3.5% for RCCPs containing 12% and 15% cement including limestone modified sand, respectively. The final water absorption for RCCPs with 12% and 15% cement included modified sand increased by 87% and 45% in comparison with RCCP containing standard sand, respectively, while final water absorption values were comparable for RCCPs with standard sand and low fines content sand.

Increasing cement from 12% to 15% decreased the initial water absorption for RCCPs containing standard sand, low fines content sand and modified sand in average of 7%, 10% and 42%, respectively. Also the final water absorption decreased about 8%, 6% and 28% for RCCPs containing standard sand, low fines content sand and modified sand, respectively.

The initial and final water absorption results for RCCP specimens revealed that 1) the low fines content sand which is not included sufficient dust fraction (sand passing the sieve #100 and #200) did not affect the initial and final water absorption of RCCP specimens significantly at both cement contents. 2) LSP increased the initial surface and final water absorption due to demand more mixing water which provides more air voids and capillary voids in cement paste. 3) increasing cement from 12% to 15% can slightly affect the initial surface and final water absorption of RCCPs containing standard sand and low fines content sand, while those values for RCCPs containing modified sand were influenced strongly.

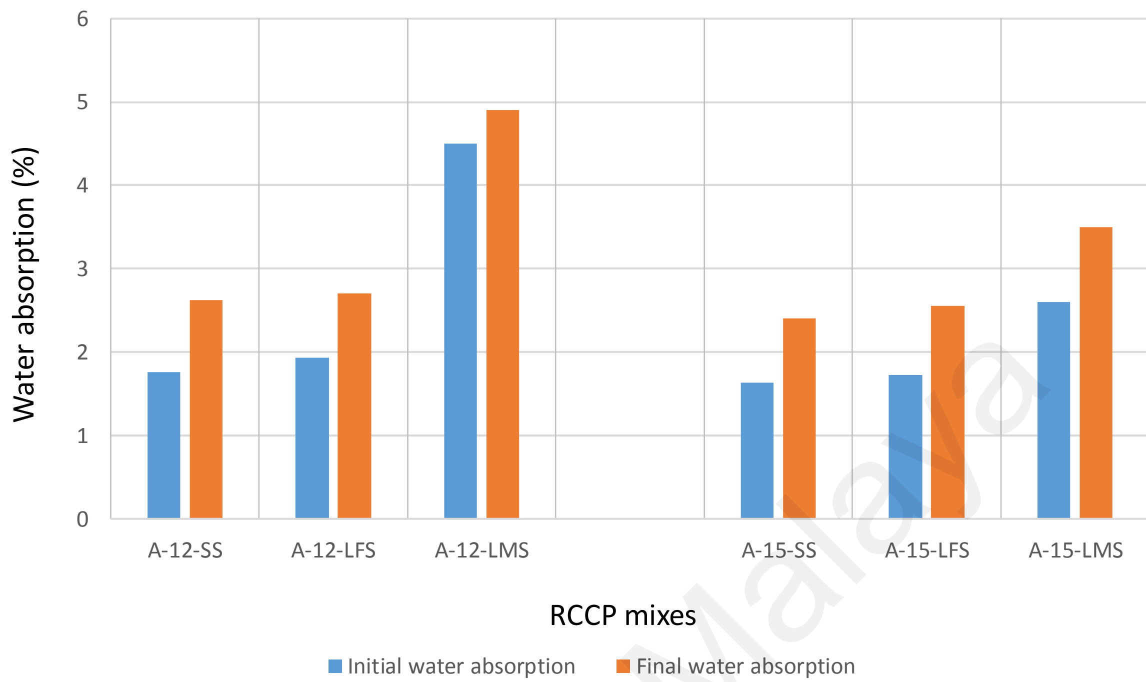


Figure 4.25: Initial and final water absorptions of the RCCPs

4.3.1.6 Porosity

Porosity results of the RCCPs is presented in Figure 4.26. It can be seen that the porosity of RCCPs with 12% cement containing low fines content sand and modified sand increased by 12% and 100% in comparison with RCCP containing standard sand. Also, the porosity for RCCPs with 15% cement containing low fines content sand and modified sand raised by 7% and 33%. It could be concluded that the porosity of RCCP can be influenced slightly by low fines content sand. However, the limestone modified sand affected the porosity of RCCP strongly that is resulted from higher mixing water. The increase in total porosity resulting from increasing water to cement ratios (Mehta, 1986). RCCP with lower porosity result in high compressive strength and durable concrete (Topličić-Ćurčić et al., 2015). However excess porosity allows the penetration of air, water, and aggressive ingredients and reduces the durability of concrete in harsh environment (Khayat & Libre, 2014).

As such as water absorption of RCCP specimens, increasing cement from 12% to 15% decreased porosity values about 2%, 6% and 35% for RCCPs containing standard sand, low fines content sand and modified sand, respectively. However, this reduction for standard sand and low fines content sand RCCPs was not considerable, while it was a significant decline for RCCP containing modified sand.

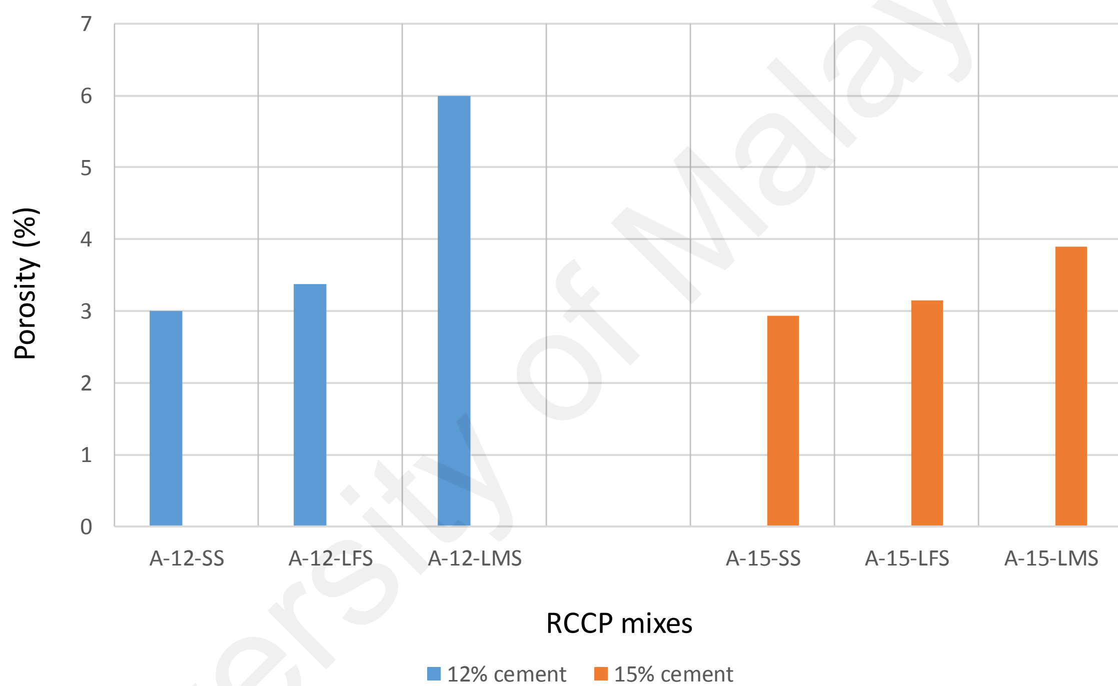
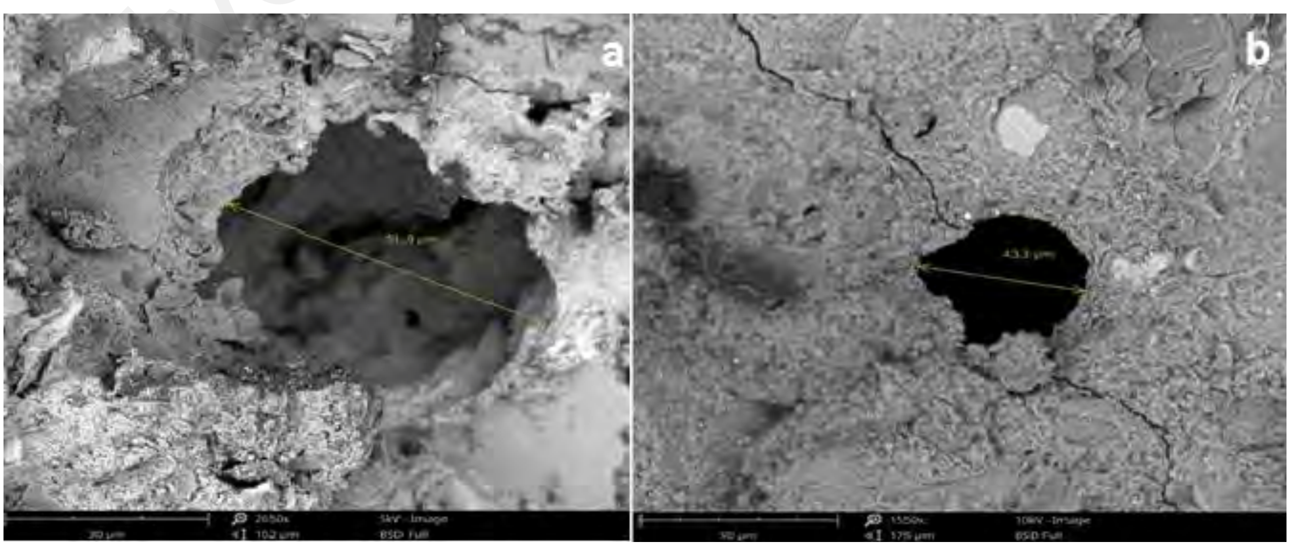


Figure 4.26: Porosity for RCCPs containing 12% and 15% cement at 28-day ages

4.3.1.7 Scanning Electron Microscope (SEM) Test

The hydrated cement paste contains different types of voids. These voids significantly influence hydrated cement paste properties. Entrapped air voids may be as large as 3 mm and entrained air voids usually range from 50 to 200 μm (Mehta, 1986). The SEM images of RCCPs containing standard sand, low fines content sand and modified sand are shown in Figure 4.27. AS can be seen the RCCP specimens with 12% and 15% cement containing standard sand showed the void sizes between 15 and 52 μm. Also, those values for 12% and 15% cement RCCPs containing low fines content sand and modified sand were around 15-90 μm and 95-300 μm, respectively. However, increasing cement from 12% to 15% influenced the void sizes especially RCCPs containing modified sand. The biggest voids size decreased from 52 to 43 μm for standard sand, from 90 to 78 μm for low fines content sand and 300 to 120 for modified sand when the cement content increased from 12% to 15%, respectively.

The SEM results has proven that 1) the dust fraction (sand passing the sieve #100 and #200) can affect the void sizes but not significantly. It means that the void sizes increment in the absence of dust fraction do not have a determinative role for fresh and hardened strength of RCCP 2) although increasing cement has a positive role for RCCP containing standard sand and low fines content sand but this effect is not considerable and it cannot be justified economically. However, cement increment was more useful for RCCP containing limestone modified sand 3) the void sizes could be influenced by mixing water strongly. The water to cement ratio, and the age of cement hydration significantly affect pore size distributions. Generally, large pores influence the compressive strength and permeability, while small pores influence mostly the drying shrinkage and creep (Mehta,1986).



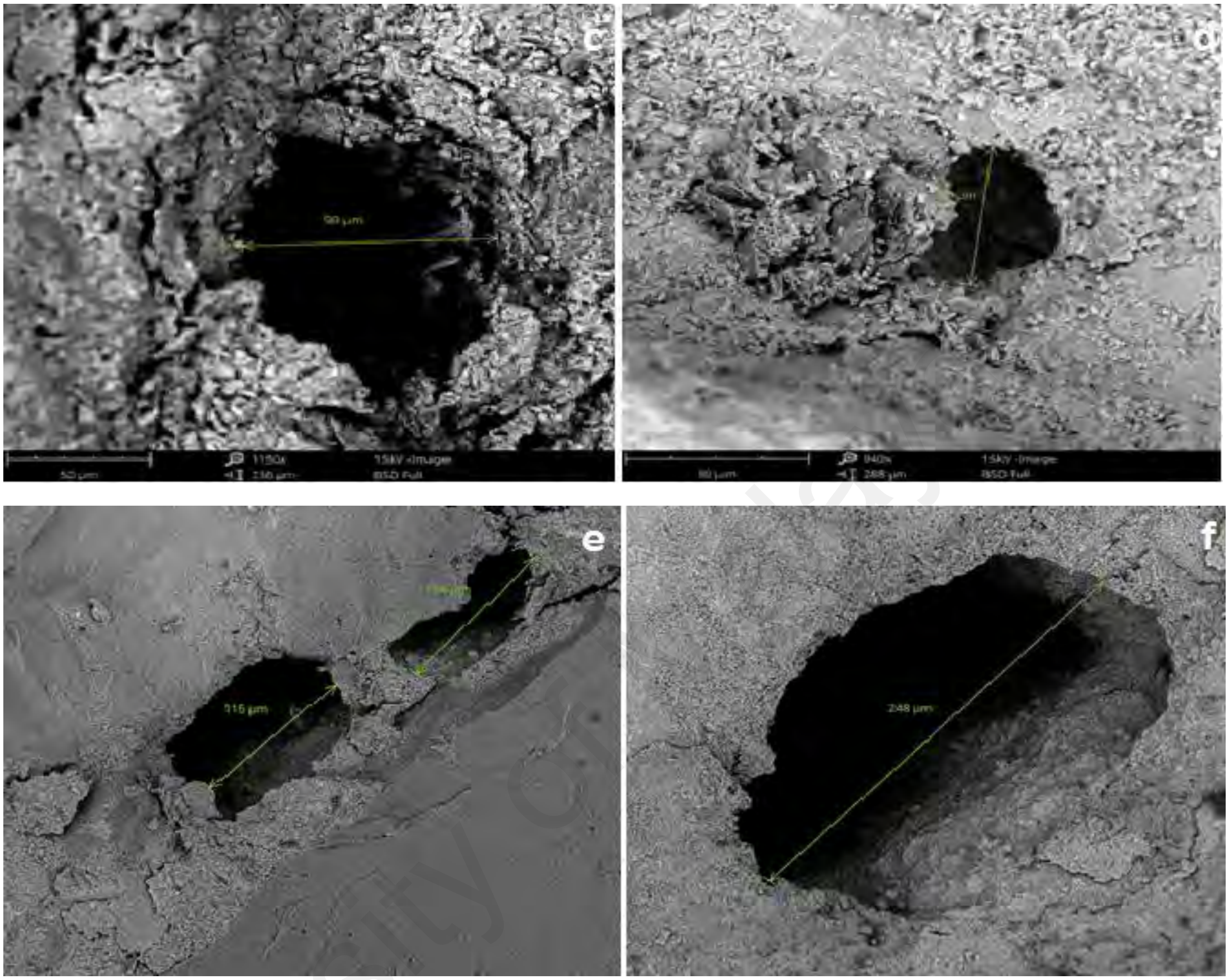


Figure 4.27: Void sizes in the paste of RCCPs. a: A-12-SS; b: B-15-SS; c: A-12-LFS; d: B-15-LFS; e: A-12-LMS; f: B-15-LMS

4.3.1.8 Ultrasonic pulse velocity

Ultrasonic Pulse Velocity (UPV) method is particularly effective allowing in-depth analysis of material homogeneity (Lorenzi et al., 2015). UPV tests are very sensitive to homogeneity and density variations and can provide important data for decision making about the conditions of concrete structures (Lorenzi et al., 2015). The range of UPV qualitative rating varies from 3 to 4.5 Km/s (IS 13311, Part I). For excellent quality concrete, good quality concrete and medium quality concrete the UPV must be more than 4.5 Km/s, varying between 3.5-4.5 Km/s and between 3.0–3.5 Km/s, respectively. In this study, the UPV was about 4.72 and 4.61 Km/s for RCCPs containing standard sand with 15% and 12% cement, respectively. Therefore, RCCPs with standard sand were in the range of excellent quality concrete. Also, this value for RCCPs containing low fines content sand with 15% and 12% cement was around 4.54 and 4.43 Km/s, respectively. However, the UPV value for RCCPs containing modified sand with 15% and 12% cement decreased by 4.1 and 3.9 Km/s, respectively. It can be concluded that uniformity, quality and density of RCCP may not be affected by low fines content sand significantly. In addition, increasing cement from 12% to 15% has a positive effect on the quality and providing dense structure in RCCP production.

4.3.1.9 Specific heat capacity

Specific heat (c-value) states the heat storage capability of concrete per unit mass (J/kg ^{o}K). Specific heat is described as the amount of energy required to raise a unit of mass by one degree of temperature (Shafigh et al., 2018). The specific heat in this study can be estimated as follow:

$$C_p = f_{cement}\, c_{cement} + f_{aggregate}\, c_{aggregate} + f_{sand}\, c_{sand} + f_{water}\, c_{water} + f_{limestone\ powder}\, c_{limestone\ powder} \quad \text{(Eq. 4.1)}$$

Where the specific heat of cement, granite aggregate, sand, water and limestone powder are 753.6, 790, 759.5, 4186.6 and 837.3 J/kg ^{o}K, respectively (Choktaweekarn et al., 2009; Elmi et al., 2017)

The c-value of samples based on experimental measurement and theoretical estimation are summarized in Table 4.1 The comparison between experimental and calculated values represents that the sample with standard sands have the lower error. The c-value estimation through the law of admixture just consider the c-value of raw material regardless the amount of porosity. However, in real conditions the porosity of specimens have been increased by using non-standard sands and limestone powder. It seems the estimated c-value through Eq.4.1 is more precise for samples with low porosity.

Table 4.1 The c-value of different samples

Sample (ID)	Calculated c-value (J/kg ^{o}K)	Measured c-value (J/kg ^{o}K)	Error (%)
A-12-SS	944.2	981.6	3.9
A-12-LFS	944.2	986.3	4.4
A-12-LMS	963.7	1053.4	9.3
B-15-SS	979.0	1007.2	2.8
B-15-LFS	979.0	1018.4	4.0
B-15-LMS	985.6	1097.5	11.3

4.4 Optimum moisture content in roller-compacted concrete pavement

4.4.1 Results and analysis

4.4.1.1 Fresh properties

Based on visual inspections, no segregation was observed for all mixes during mixing, placing and compaction. Sufficient workability for all RCCPs except RCCP at 4.5% moisture content was observed. Sufficient workability is crucial for RCCP's easy compaction, uniform density, bonding with a previous layer and also for the support of compaction equipment (Yerramala & Babu, 2011). There was no joint separation for all specimens at different moisture contents during the split tensile strength test.

Figure 4.28 shows the Vebe times of the RCCP mixtures prepared at different moisture contents. Vebe time is defined as the time that cement mortar appears at the surface of the surcharge (Fakhri & Amoosoltani, 2017). As seen in Figure 4.36, as moisture content increases from 4.5% to 7%, the Vebe time from decreases 45 sec to 22 sec. According to the fresh and hardened properties of RCCPs, the Vebe time between 32 sec and 39 sec shows more desirable performance. Based on ACI 325 Vebe time is limited to 30-40 s for the production of RCCP.

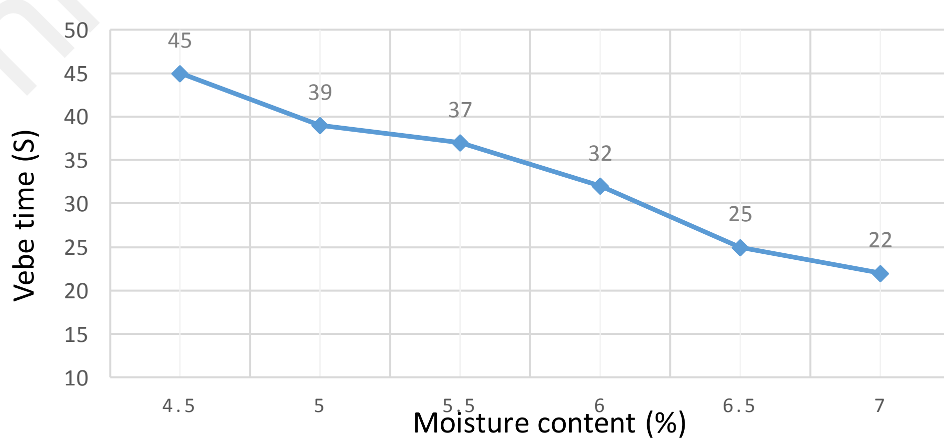


Figure 4.28: Relation between moisture content and Vebe time of RCCPs

4.4.1.2 Density

Table 4.2 presents and compares the oven dry density values of RCCPs which made according to the soil compaction concept and vibrating hammer method. The oven dry density values of RCCPs which made based on the soil compaction concept and vibrating hammer method were in the range of 2265-2380 Kg/m^3 and 2271-2398 kg/m^3, respectively. Generally, the density of the RCCP ranged from 2340 to 2510 kg/m^3 (Khayat & Libre, 2014). It can be concluded that compaction with vibrating hammer method for RCCP can provide higher pack density in comparison with soil compaction concept.

Table 4.2: The oven dry density based on the soil compaction concept and vibrating hammer method

Oven dry density based on soil compaction concept (kg/m^3)	Oven dry density based on vibrating hammer method (kg/m^3)
2265	2271
2366	2374
2380	2398
2372	2384
2333	2344
2273	2288

4.4.1.3 Compressive strength

Figure 4.29 presents the results of compressive strength test according to the vibrating hammer method and soil compaction concept at 1, 7 and 28 days. RCCPs which are designed according to vibrating hammer method and soil compaction concept showing the maximum compressive strengths of 19.5, 30.8, 38.9 MPa and 18.1, 28.3, 36.1 MPa at 1, 7 and 28 days, respectively, with a standard deviation of 2% to 8%. As seen in the figure, the compressive strength increases as the moisture content increases from 4.5% to 5%, exhibiting the highest compressive strength at 5% at all curing ages. Then, the compressive strength gradually decreases as the moisture content increases from 5% to 7%. In addition, the compressive strength of mixtures which made according to vibrating hammer method showing higher compressive strength value in comparison with soil compaction concept at the same moisture content.

At 28-day ages the compressive strength of RCCPs which are made according to the vibrating hammer method and soil compaction concept increases about 26% and 29% as the moisture content increases from 4.5% to 5%, and then it decreases about 6% and 4% when the moisture content increases from 5% to 5.5%. Afterward, by increasing moisture content from 5.5% to 6% the compressive strength is almost constant. Finally, an increase of moisture content from 6% to 7% leads to a decrease of the compressive strength by about 16% and 13%, respectively.

Although the maximum dry density at both vibrating hammer method and soil compaction concept is corresponding to about 5.7% moisture content, the highest compressive strength is obtained at 5% moisture content. It might be due to the following reasons. First, lower water content results in lower air voids and capillary voids that provide higher strength concrete. An inverse relationship between porosity and strength in concrete is reported (Mehta, 1986). Porosity and pore size distribution of RCCP depend on the water-to-cement ratio and the degree at which the concrete is compacted (Khayat & Libre, 2014). The hydrated cement paste can contain different types of voids that significantly influence its properties. The entrapped air voids and capillary voids in a hydrated cement paste depend on the amount of mixed water with the cement, can affect the hardened properties of concrete adversely (Mehta, 1986). Second, a proper selection of moisture content that is sufficient to achieve good workability and adequate compaction could prevent from compaction voids. Compaction is the main factor affecting the hardened properties of RCCP (Khayat & Libre, 2014). In this research, although increasing water content from 5% to 5.7% leads to a decrease of Vebe time by 10%, RCCP at 5% water content provides sufficient workability and no compaction voids are observed. It is important to note that several compaction voids are observed in RCCP at 4.5% moisture content. A proper selection of binder composition, and more importantly ideal moisture content of the mixture not only reduce a significant number of compaction voids but also improve the durability performance of RCCP (Khayat & Libre, 2014).

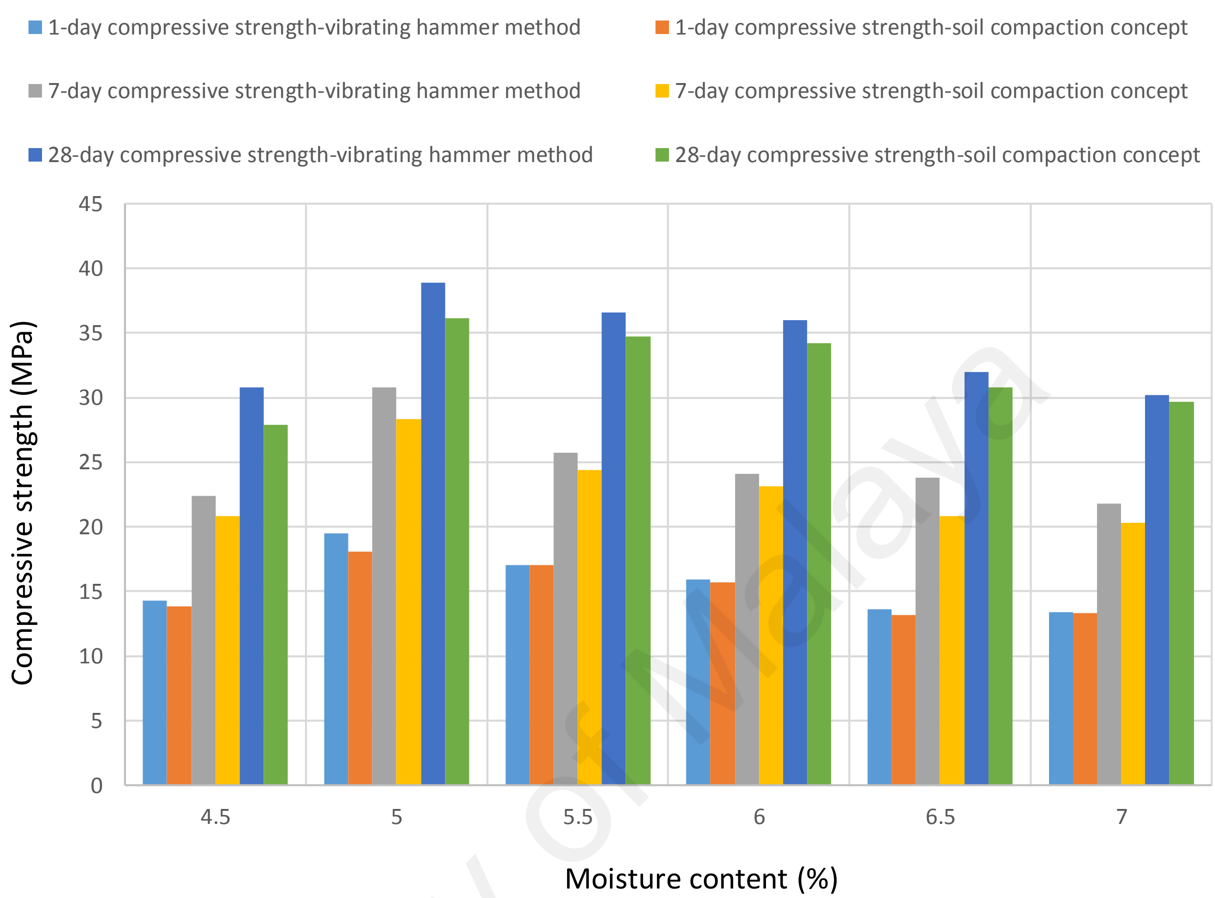


Figure 4.29: Compressive strength for RCCP specimens with different moisture contents according to the vibrating hammer method and soil compaction concept

The relationship between 28-day compressive strength and density is presented in Figure 4.30. The figure shows a good correlation between 28-day compressive strength and density.

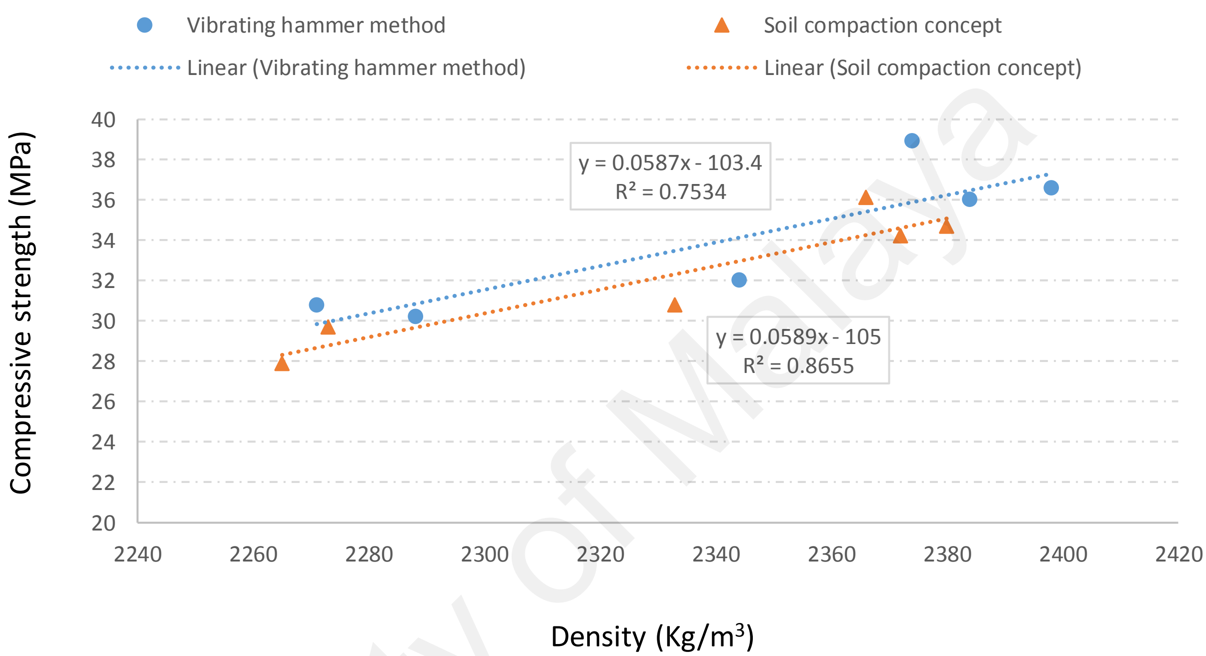


Figure 4.30: Relationship between 28-day compressive strength and density

4.4.1.4 Splitting tensile strength

The splitting tensile strengths of RCCPs according to the vibrating hammer method and soil compaction concept at 1, 7 and 28 days are shown in Figure 4.31. The standard deviation for the splitting tensile strength measurements is ranged from 2% to 6%. The results illustrate the same trend with the compressive strength, showing the highest strength value at 5% moisture content, and then a downward trend as the water content increases from 5% to 7%. At 28-day ages, the splitting tensile strength of RCCPs which are prepared according to the vibrating hammer method and soil compaction concept rose about 32% and 42% when the water content increased from 4.5% to 5%, then an increase of water content from 5% to 5.5% exhibits a slight decline about 8% and 4% in the splitting tensile strength, respectively. Afterward, the splitting tensile strength is almost constant from 5.5% to 6%. Increasing water content from 6% to 7% leads to a decrease of splitting tensile strength by about 16% and 15%, respectively.

Based on these observations, it can be concluded that additional water content after 5%, in spite of the optimum water content of 5.7%, does not have a positive contribution on the strength gain. In other words, the water content lower than the optimum moisture content in RCCP may be more appropriate to obtain maximum splitting tensile strength.

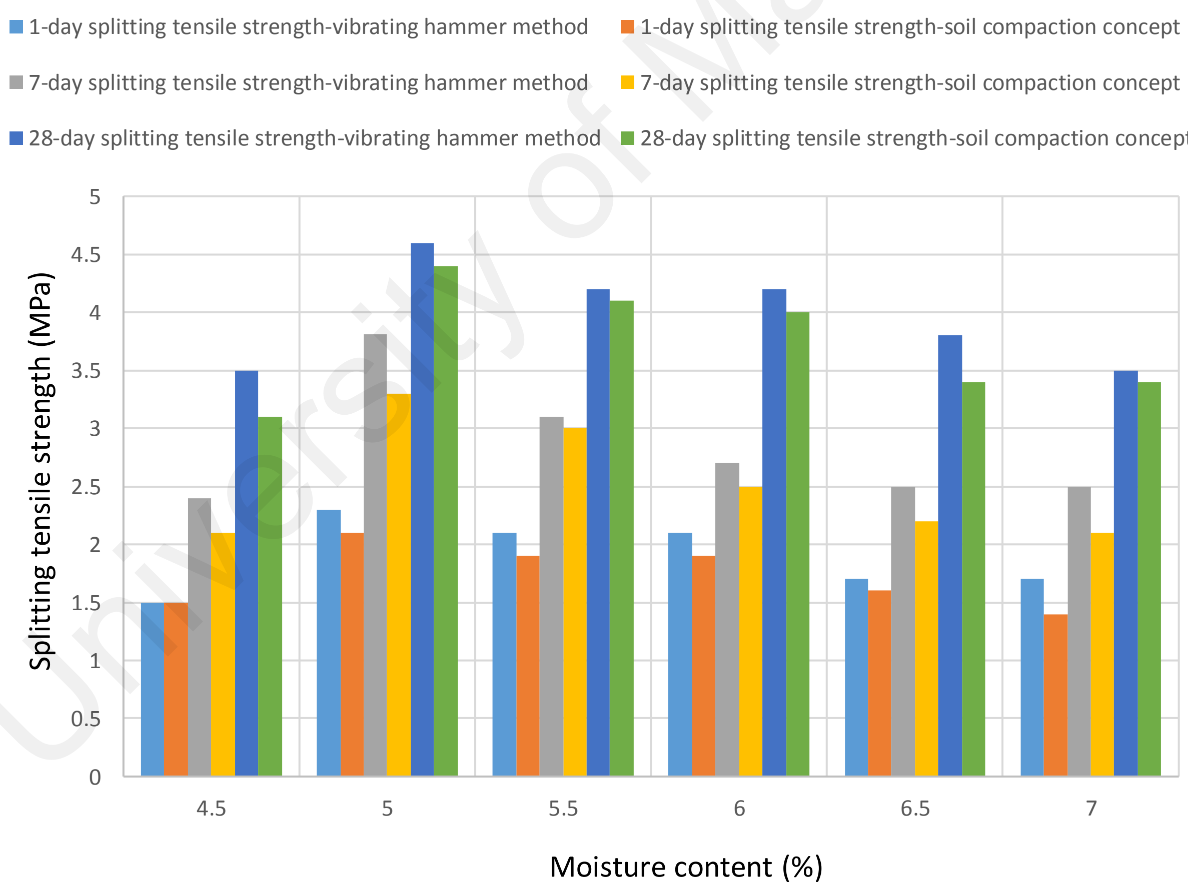


Figure 4.31: Splitting tensile strength for RCCP specimens with different moisture contents according to the vibrating hammer method and soil compaction concept

4.4.1.5 Flexural tensile strength

Flexural tensile strength is a critical performance index in RCCP mixtures because it affects not only design results such as pavement thickness but also the resistance of mixture against fatigue and thermal cracking (Fakhri & Amoosoltani, 2017). Figure 4.32 shows the results of flexural tensile strength of mixtures which made according to the vibrating hammer method. The standard deviation for the flexural tensile strength is ranged from 2% to 6%.

In this research the flexural tensile strength shows the maximum at 5% moisture content at all ages. At 28 days, the flexural tensile strength increases sharply from 4.1 to 5.5 MPa when the water content increased from 4.5% to 5%. Then it decreases slightly to 5.25 MPa and 5.1 MPa at 5.5% and 6% of moisture content, respectively. The flexural tensile strength decreases to 4.3 MPa at both 6.5% and 7% water content.

In this research the flexural tensile strength at 28 days is ranged from 4.1 to 5.5 MPa and the ratio of compressive strength to flexural strength is about 0.14. In typical concrete, the flexural tensile strength is about 15% of the compressive strength (Li, 2004). In addition, the flexural tensile strength of RCCP, depending on the mix design, is generally ranged from 3.5 to 7 MPa (Harrington et al., 2010).

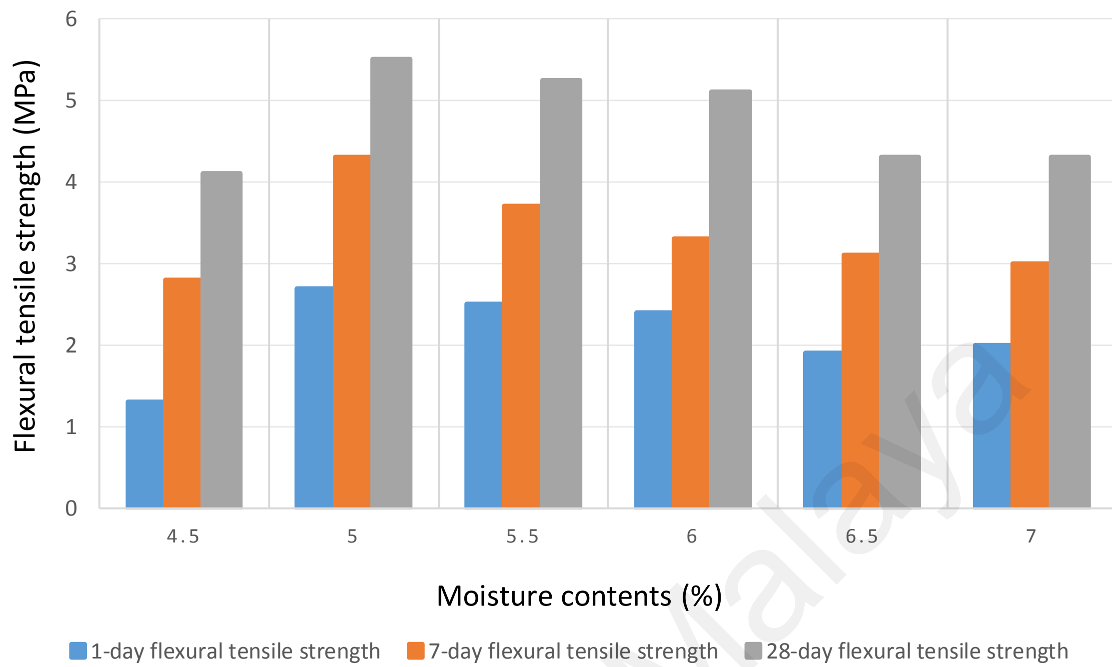


Figure 4.32: Flexural tensile strength for RCCP specimens with different moisture contents according to the vibrating hammer method

4.4.1.6 Water absorption

Pore structure of cement paste significantly affects the water absorption of concrete (Zhang & Zong, 2014). A passage for fluid into concrete is through pore network channels in cement paste matrix (Ramli & Tabassi, 2012). It has been reported that water absorption decreases with decreasing the water to cement ratio, with increasing curing time, and with increasing a degree of consolidation (Mehta, 1986; Mohammadi, 2013).

The results for initial and final water absorption for the mixtures which prepared according to the vibrating hammer method and soil compaction concept at different moisture content are presented in Figure 4.33. As seen in the figure, the water absorption values at 4.5% moisture content is the maximum, while the 5% moisture content shows the least water absorption. Increasing moisture content from 5% to 7% leads to an increase from initial to final water absorptions by 47% and 35% for RCCPs which made according to the vibrating hammer method and 40% and 34% for RCCPs which made according to the soil compaction concept, respectively. The reason might be a reduction of pores because lower water content makes lower pore space and decreases the permeability of the RCCPs. However, further decreasing of water content can lead to insufficient workability of RCCP, causing compaction voids and high water absorption values. Finally, it can be concluded that decreasing the moisture content in RCCP by an optimum amount can reduce the water absorption, but too low moisture content can cause improper compaction which can create many compaction voids. A high number of compaction voids may create an interconnected network that seriously jeopardizes durability performance of concrete (Khayat & Libre, 2014).

CEB (1989) divided concrete's performance into three categories based on water absorption: (1) Good with water absorption < 3%, (2) Average with water absorption 3-5% and (3) Poor with water absorption > 5%. As it can be seen, the initial water absorption of all RCCPs are lower than 3%. The final water absorption at 5%, 5.5% and 6% moisture content indicates values lower than 3%. However, the final water absorption is between 3% and 4% for the RCCPs at 4.5%, 6.5% and 7% moisture content.

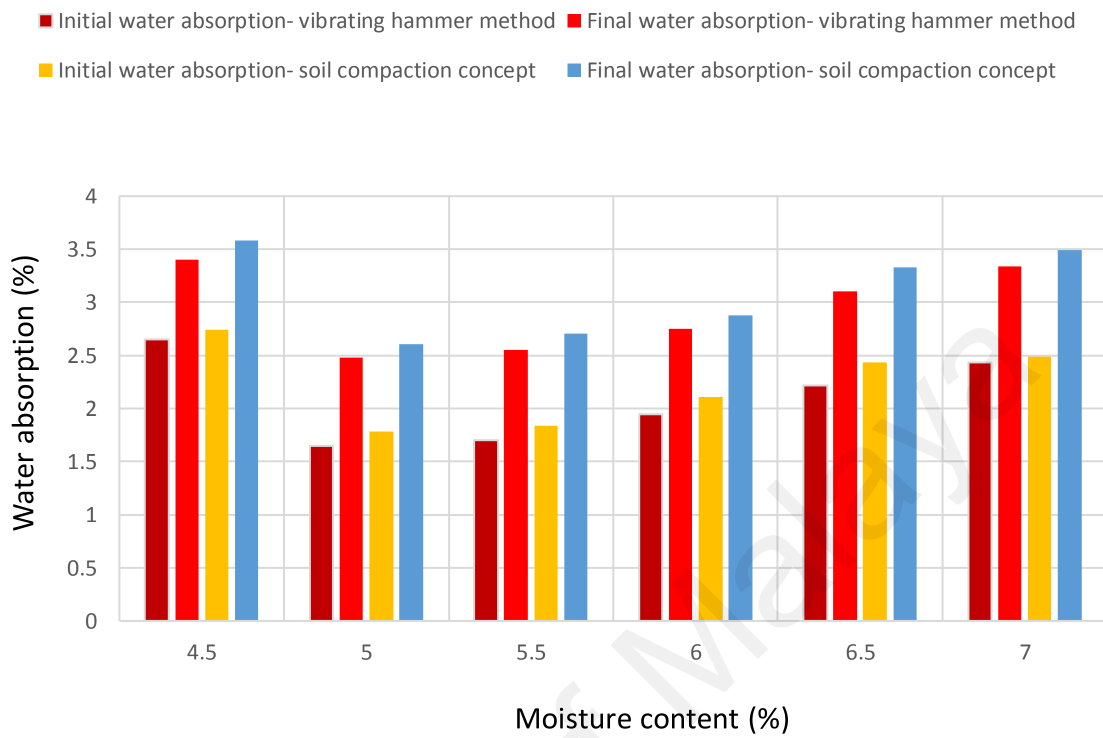


Figure 4.33: The water absorption values for RCCP specimens with different moisture contents according to the vibrating hammer method and soil compaction concept

4.4.1.7 Porosity

Porosity measurement can be a method to calculate the total volume of capillary voids (Mehta,1986). Low water to cement ratios result in a dense structure of the hardened cement paste as the number of capillary pores is reduced (Hüsken, 2010). In general, low porosity concrete leads to high strength and long term durability (Kokubu,1996).

In this study the variation of porosity is similar to the water absorption. Figure 4.34 shows the porosity measurements of RCCPs with different moisture contents. As seen in the figure, the lowest porosity percentage is at the 5% moisture content and the highest is at the 4.5% moisture content at both vibrating hammer method and soil compaction concept. However, increasing moisture content from 5% to 7% increases the porosity by about 35%

and 32% for RCCPs which made according to vibrating hammer method and soil compaction concept, respectively. The reason might be an increment of pores structure due to the increased moisture content in RCCP. Kuzu et al (1990) recommended that the porosity of roller compacted concrete is less than 3%. There are also two potential mechanisms to explain the reduction of porosity in concrete. First, better packing of the particles in the fresh state leads to low porosity in concrete (Domone & Illston, 2010). From this viewpoint, proper compaction during RCCP construction is the key to obtain high packing density. Second, a low water-to-cement ratio can provide high ultimate strengths by reducing porosity and limiting the ability of free water to penetrate (Hodgson, 2000). Thus, it can be concluded that the high density mixture with lowest moisture content, but providing sufficient workability, should be considered in RCCP construction.

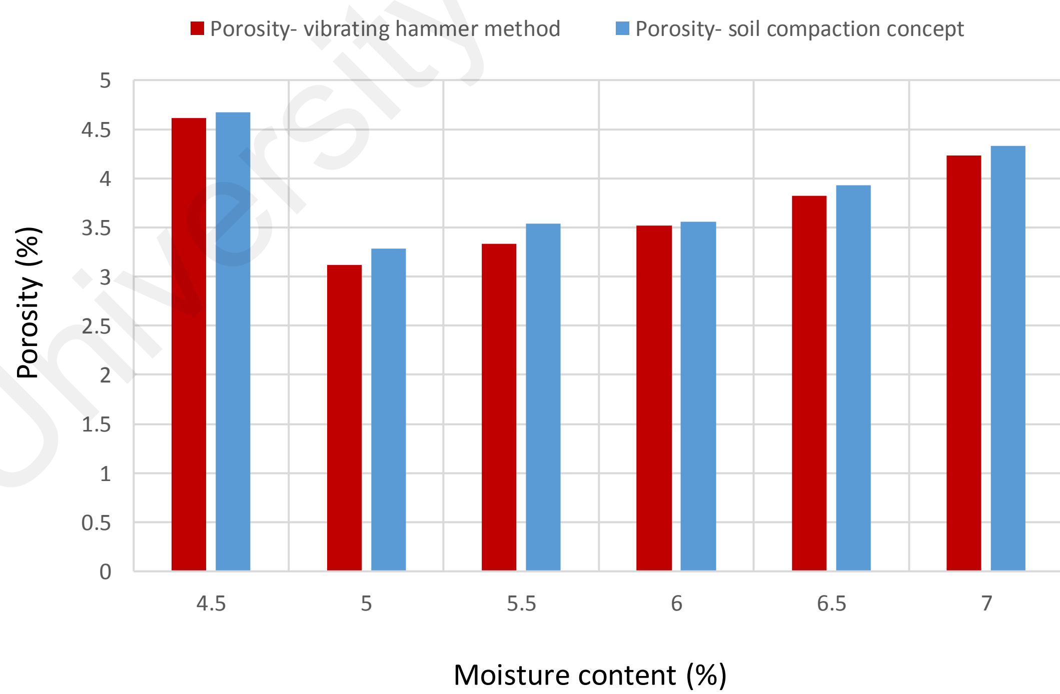


Figure 4.34: The porosity percentages for RCCP specimens with different moisture contents according to the vibrating hammer method and soil compaction concept

The relationship between 28-day compressive strength and porosity is presented in Figure 4.35. The figure shows a strong correlation between 28-day compressive strength and porosity. It has been reported that an increment of 1% in the concrete porosity reduces the compressive strength about 3-5 MPa (Kokubu, 1993). In this research an increment of about 1% in the porosity of RCCP leads to approximately 8-MPa reduction in the 28-day compressive strength. Therefore, these results indicate that RCCP is more sensitive to mixed water content than conventional concrete.

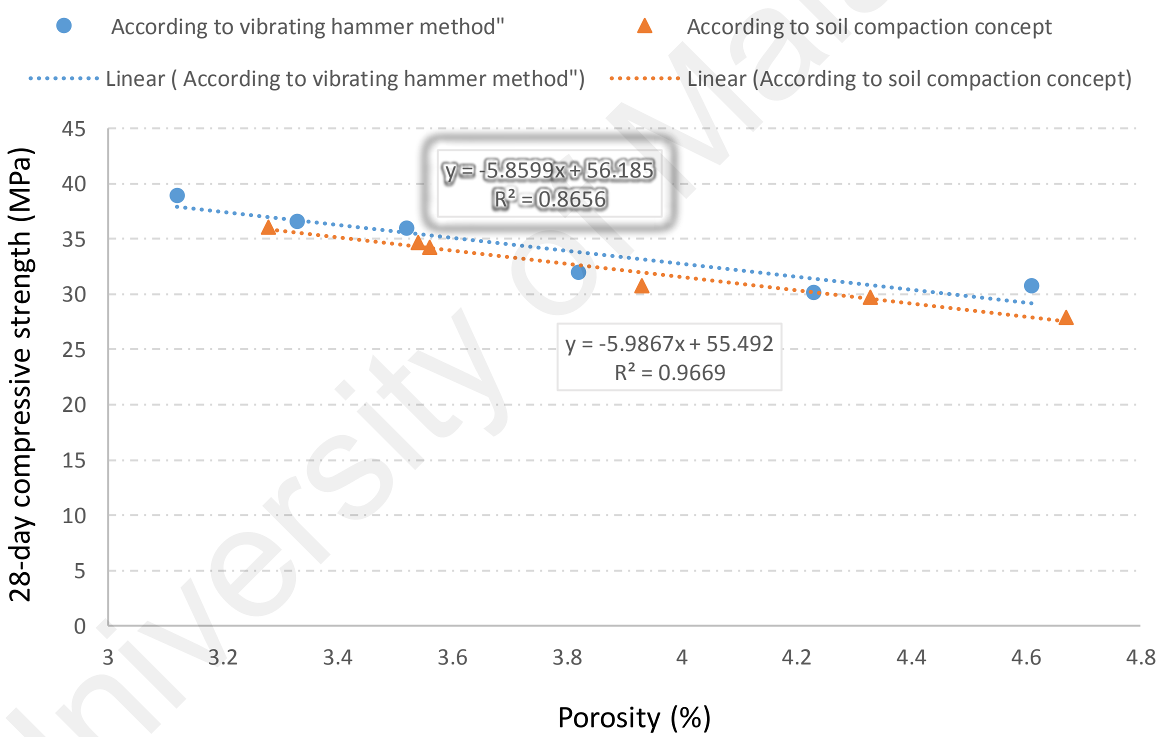


Figure 4.35: Relationship between 28-day compressive strength and porosity

4.4.1.8 Field Emission Scanning Electron Microscope (FESEM) Test

The durability of concrete depends on the characteristics of its pore structure (De Schutter & Audenaert, 2004) and it is obtained when pore structure gets tight and highly impermeable (Kolyvas, 2007). In order to investigate the influence of moisture content on the microstructure of RCCP, FSEM test was conducted on RCCPs prepared at different moisture contents. The FESEM test was used to detect entrapped air voids and compaction voids in those RCCP specimens which made according to vibrating hammer method and the FESEM images are shown in Figures 4.36 and 4.37. Entrapped air voids occur as a result of mixing, handling or placing of concrete. Those entrapped air voids may be as large as 3 mm and it adversely affects the strength of concrete (Mehta, 1986).

As seen in Figure 4.45, several compaction voids are observed in the RCCP with 4.5% moisture content and the diameter of those voids are ranged from 38 µm to 330 µm. Losing at least five percent of concrete's long-term strength may happen because of each percent of voids retained in the concrete due to compaction deficiencies (Kalantari et al.,2009). On the other hand, compaction voids are rarely observed in the RCCPs with more than 4.5% moisture content. The maximum diameter of entrapped air voids observed in the RCCPs with 5%, 5.5%, 6%, 6.5% and 7% moisture contents are 32 µm, 45 µm, 97 µm, 200 µm and 295 µm, respectively (see Figure 4.38). This trend shows that the pore structure of RCCP with 5% moisture content is improved and the matrix is densified; however, increasing the mixed water in RCCP construction may create larger entrapped air voids.

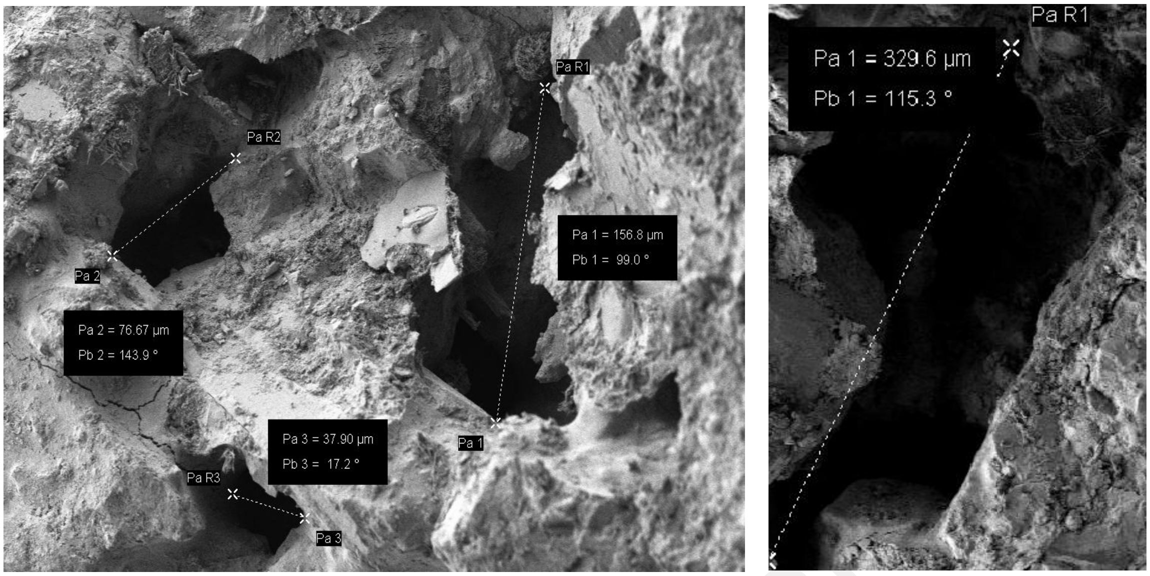
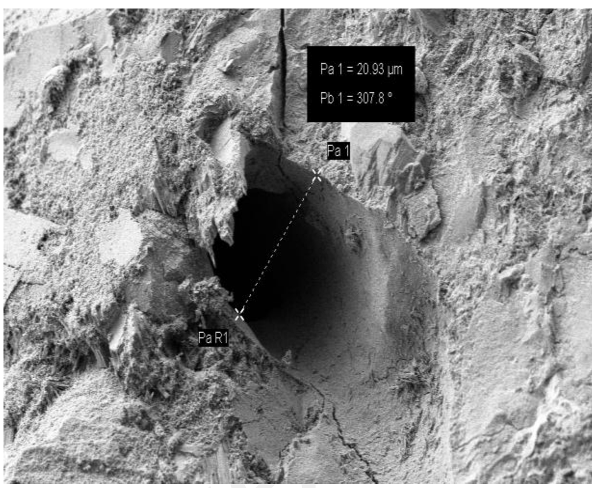
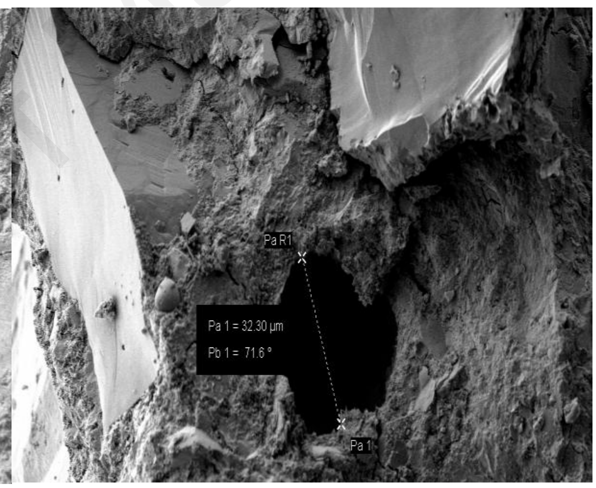


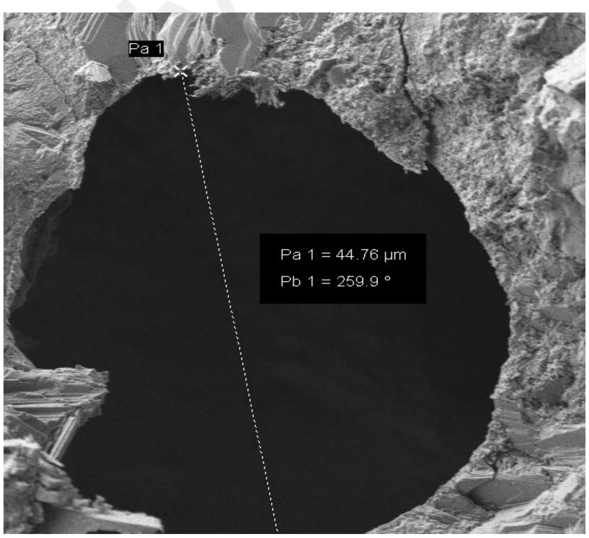
Figure 4.36: Compaction voids in 4.5% moisture content RCCP



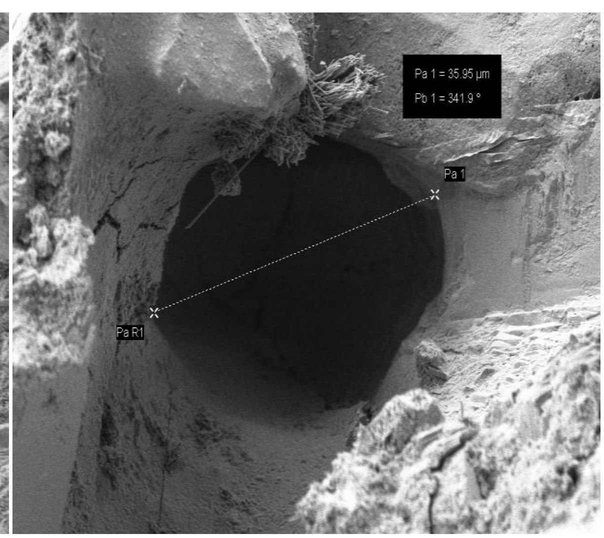
(1)



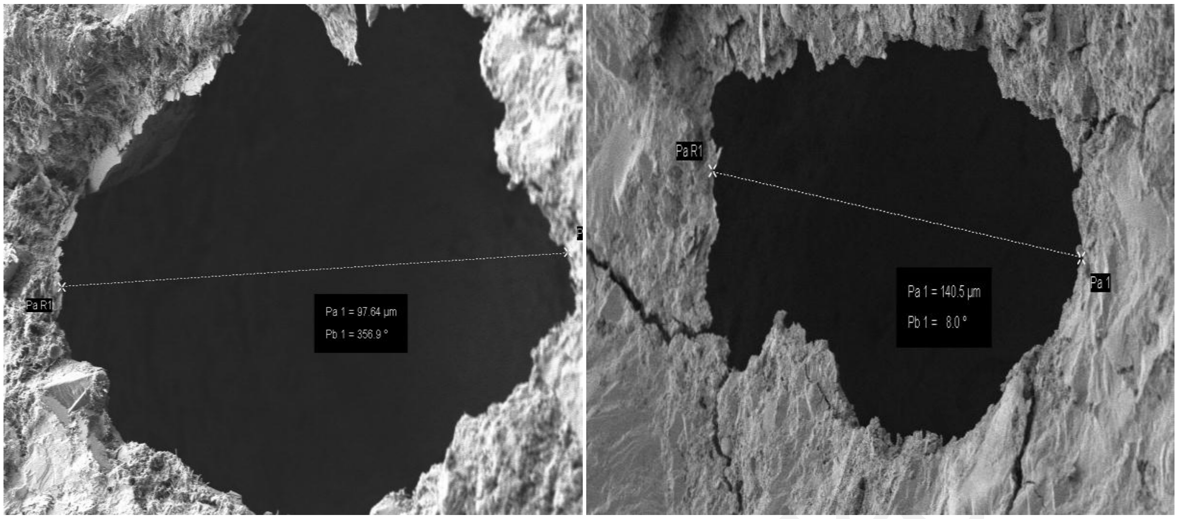
(2)



(3)



(4)



(5) (6)

Figure 4.37: Void sizes in the paste of RCCPs. 1,2: Entrapped air voids in 5% moisture content RCCP; 3,4: Entrapped air voids in 5.5% moisture content RCCP; 5: Entrapped air voids in 6% moisture content RCCP; 6,7: Entrapped air voids in 6.5% moisture content RCCP; 8: Entrapped air voids in 7% moisture content RCCP

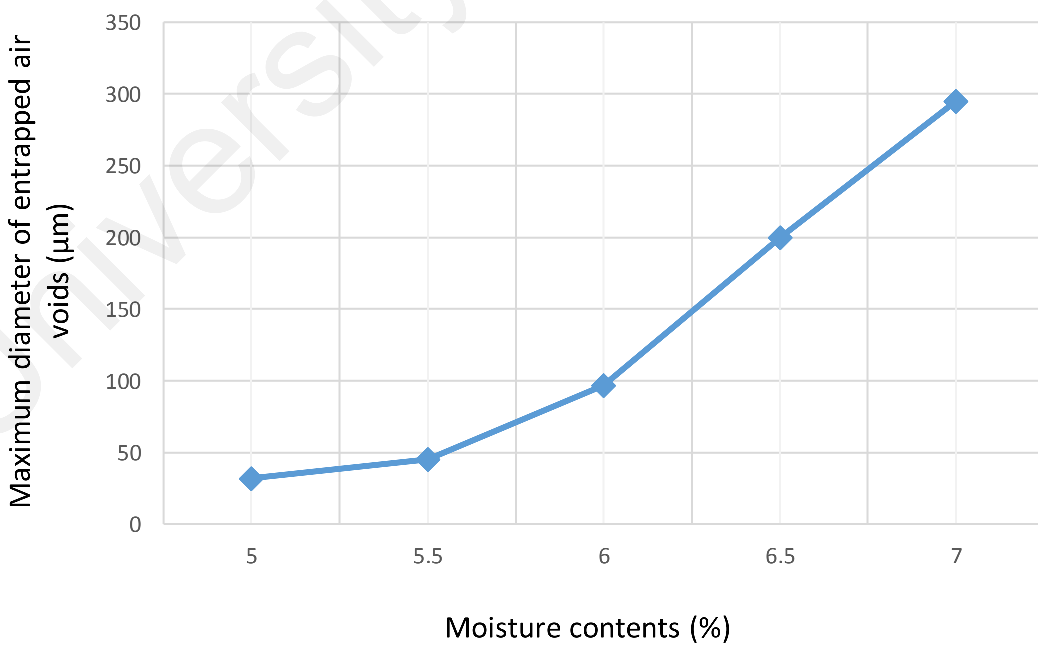


Figure 4.38: The maximum diameter of entrapped air voids for RCCP specimens with different moisture contents

4.5 A comparison between roller-compacted concrete pavement and normal vibrated concrete

4.5.1 Results and analysis

4.5.1.1 Fresh properties

The measured fresh properties of all the mixtures are summarized in Table 4.3. The Vebe time for RCCPs was in the range of 26-29 sec. Based on ACI 325 the Vebe time is limited to 30-40 sec for producing RCCP. Figure 4.39 shows the RCCP surface texture at the time of Vebe test and sufficient workability for RCCP mixes was observed. Sufficient workability is crucial for RCCP's easy compaction, uniform density, bonding with previous layer and for support of compaction equipment (Yerramala & Babu, 2011).

For the NVCs, high workability of slump 200-240 mm was observed. Based on the visual inspection, no segregation or bleeding was observed for all the mixes during mixing, placing and compaction. Figure 4.40 shows the slump test for NVC mixtures. The oven dry density values of RCCP and NVC specimens were in the range of 2339-2374 Kg/m^3 and 2287-2308 kg/m^3, respectively. Generally, the density of the RCCP ranged from 2340 to 2510 kg/m^3 (Delatte, 2014).

It can be concluded that compaction with vibrating hammer for RCCP can provide higher pack density in comparison with normal vibration table for NVC. The heavy compaction applied onto RCCP results in a denser structure comparing to conventionally vibrated concrete (Khayat & Libre, 2014). The use of GGBFS decreased a slump in NVC and increased Vebe time in RCCP. It means the use of GGBFS decreased the workability in RCCP and NVC.

Table 4.3: Fresh properties for NVC and RCCP specimens

Mix	Vebe Time (S)	Slump (mm)	Oven dry density (Kg/m^3)
NVC1	N/A	239	2287
NVC2	N/A	223	2308
RCCP1	26	0	2339
RCCP2	29	0	2374

a b

Figure 4.39: (a) Surface texture of RCCP1 at Vebe test. (b) Surface texture of RCCP2 at Vebe test

c d

Figure 4.40: (c) Slump test for NVC1 (d) Slump test for NVC2

4.5.1.2 Compressive strength

Compressive strength results of the various mixes are presented in Figure 4.41. The strengths measured at 7 and 28 days show the standard deviation in the range of 2% to 6%. The compressive strengths of NVC1 at 7 and 28 days were found 35.2 and 40.1 MPa and those of NVC2 are 37.2 MPa and 42.4 MPa. However, the 7-day compressive strengths of RCCP1 and RCCP2 showed 7% and 6% decrease, respectively and the 28-day compressive strengths showed 8% and 10% increase in comparison with NVC1 and NVC2 specimens, respectively. The compressive strength of RCCP is comparable to that of NVC, typically ranging from 28 to 41 MPa. Some projects reported compressive strengths higher 48 MPa (Harrington et al., 2010).

The increase in compressive strength for NVC specimens at early ages can be attributed to the acceleration in the setting time. Early strengths may be somewhat accelerated due to better dispersion of the cement particles in water because of using superplasticizer (Mehta & Monteiro, 2006). Comparatively to the NVC it clearly can be noted that the 28-day compressive strength of RCCP mixtures is higher, about 8-10%. It should be noted, that with the use of FA and GGBFS the difference of compressive strength between NVC and RCCP is almost constant. Therefore, it can be concluded that the compressive strength of RCCP is higher than NVC, in average 9%.

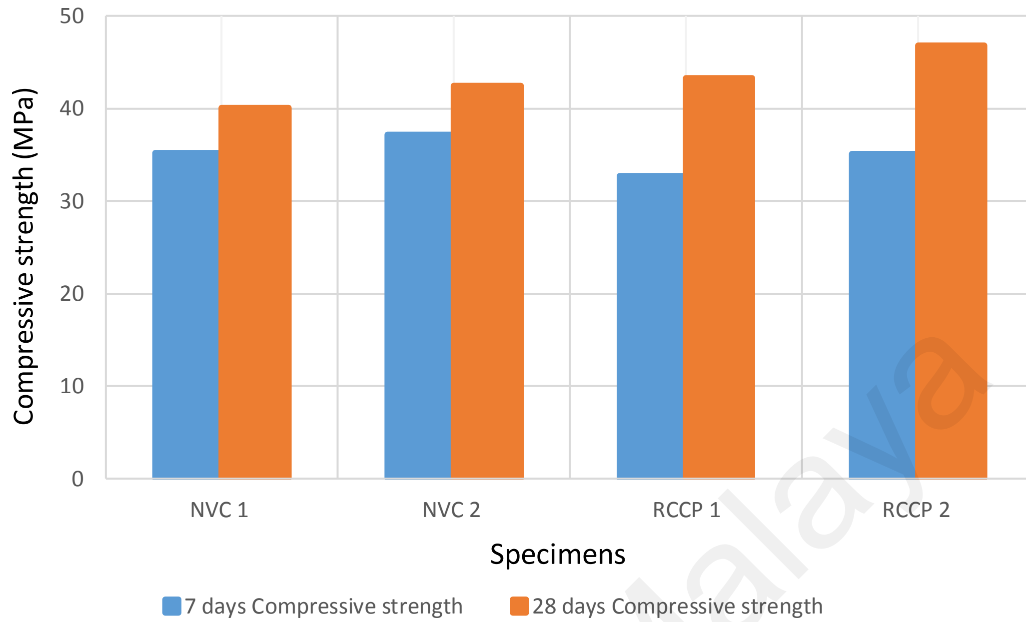


Figure 4.41: Compressive strength for NVC and RCCP mixtures

4.5.1.3 Splitting tensile strength

The splitting tensile strength results of the various mixes at 7 days and 28 days are shown in Figure 4.42. The standard deviation for the splitting tensile strength results was 3-7%. The splitting tensile strength shows the same trend with compressive strength, showing the higher values at 7 days for NVC specimens and similar enhancement in splitting tensile strength was observed for RCCP specimens at 28 days. The splitting tensile strength for RCCP1 and RCCP2 decreased about 10.2% and 9.3% at 7days and increased about 4.4% and 3.9% at 28 days in comparison with NVC1 and NVC2, respectively. These results revealed that the 28 days splitting tensile strength for RCCP mixture is comparatively higher than NVC mixture, about 4%. In addition, it can be concluded that the increment of compressive strength is higher than splitting tensile strength for RCCP mixture at 28 days, in comparison with NVC mixture.

Typically, the splitting tensile strength of conventional concrete is about 10% of the compressive strength (Li, 2004). RCCP has about the same ratio between the compressive and tensile strength as normal concrete, ranging from 7 to 13% (Mehta & Monteiro, 2006). In this investigation, the splitting tensile strength for NVC and RCCP were about 11.65% and 11.4% of the compressive strength, respectively.

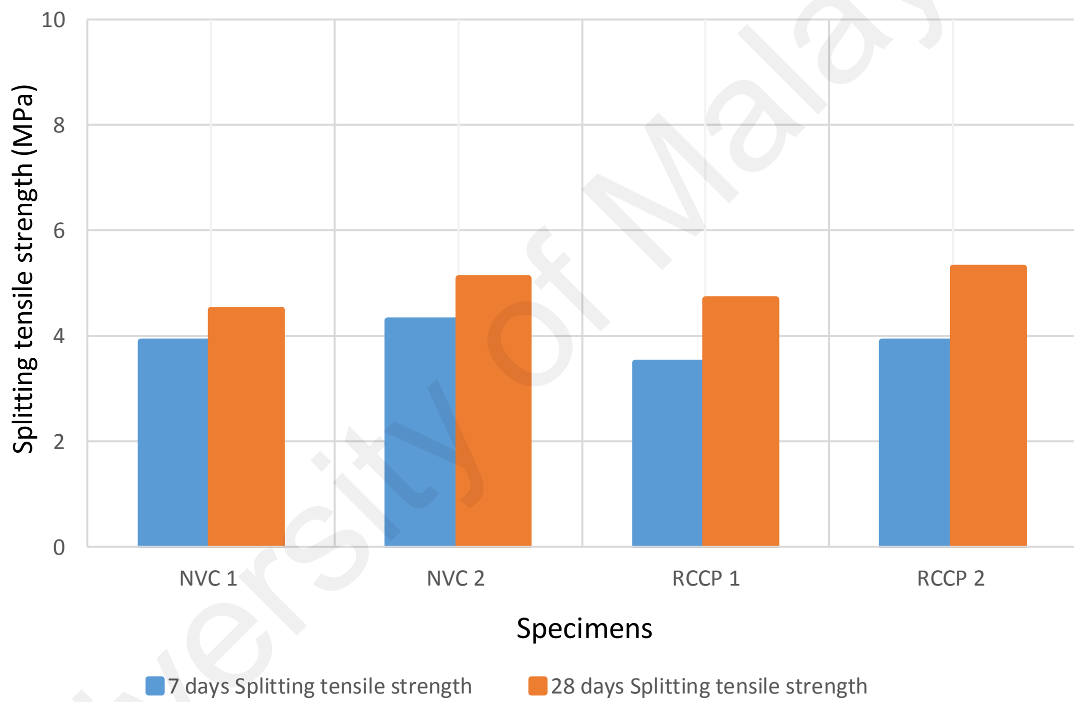


Figure 4.42: Splitting tensile strength for NVC and RCCP mixtures

4.5.1.4 Flexural tensile strength

Figure 4.43 shows the flexural tensile strength results. The standard deviation for the flexural tensile strength results were found between 3-9%. In spite of the compressive strength and splitting tensile strength, the flexural tensile strength of RCCP mixtures increased about 11.9% and 13.3% at 7 days and also increased about 19.6% and 30.1% at

28 days in comparison with NVC1 and NVC2, respectively. Flexural strength is directly related to the unit weight and compressive strength of the concrete mixture (Khayat & Libre, 2014). Since, in properly constructed RCCP the aggregates are densely packed, therefore more energy is required for crack propagation and cracking to occur (Khayat & Libre, 2014). Typically, the flexural tensile strength of conventional concrete is about 15% of the compressive strength (Li, 2004). Also, it is reported that the ratio between flexural strength and compressive strength in RCCP is about 0.15, as compared with 0.10 to 0.12 in the case of normal concrete (Khayat & Libre, 2014). In this investigation, the flexural tensile strength for NVC and RCCP were about 12.6% and 14.4% of the compressive strength, respectively.

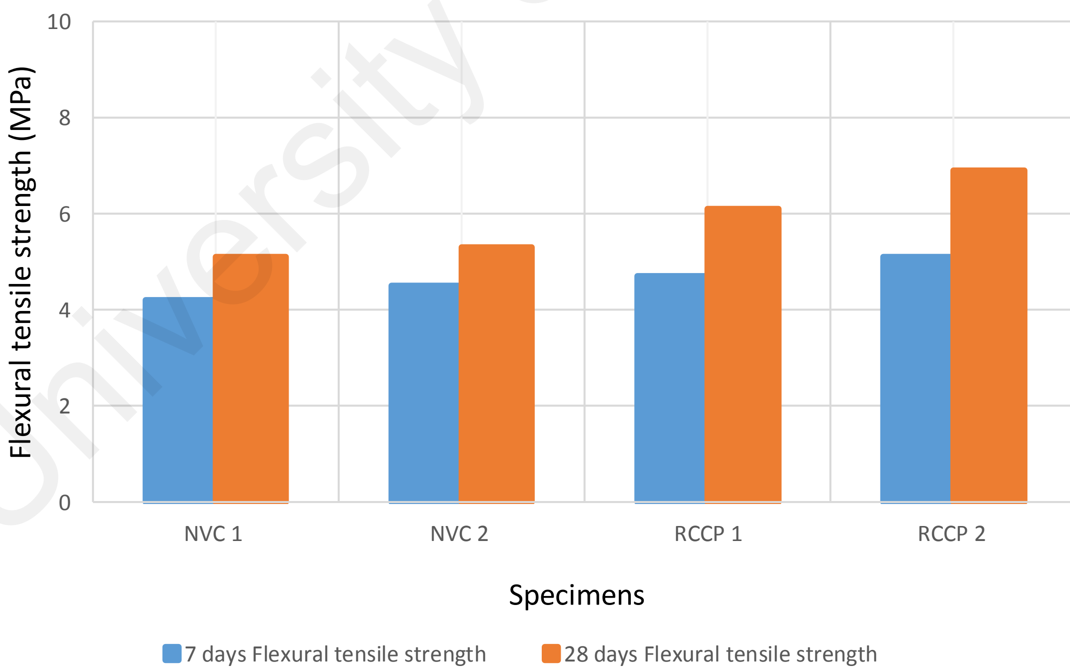


Figure 4.43: Flexural tensile strength for NVC and RCCP mixtures

4.5.1.5 Water absorption

Water absorption usually uses as an important factor for quantifying the durability of cementitious systems (Castro et al., 2011). Previous studies indicate that the water absorption values are reduced with decrease in the water-cement ratio, increase in the curing time, and increase in the degree of consolidation (Mehta & Monteiro, 2006).

The results for initial water absorption after 30 min and final water absorption after 72 h are demonstrated in Figure 4.44. As can be seen the initial surface water absorption of all RCCP and NVC mixtures showed values lower than 3%. In addition, the final water absorption for RCCP1 and RCCP2 mixtures was lower than 3%. However, it was 3.2% and 3.12% for NVC1 and NVC2 mixtures, respectively. The results revealed that initial and final water absorption for RCCP is slightly lower than that of NVC. Also, Khayat and Libre (2014) compared the water absorptions of the RCCP mixtures with that of the conventional concrete. In this study, lower water absorption was observed in the RCCP mixture comparing to conventional concrete.

The final water absorption for RCCPs containing FA and GGBFS reduced about 7% and about 9%, respectively. It should be noted that the initial and final water absorption for NVC and RCCP mixtures containing GGBFS were slightly lower than that of mixtures containing FA.

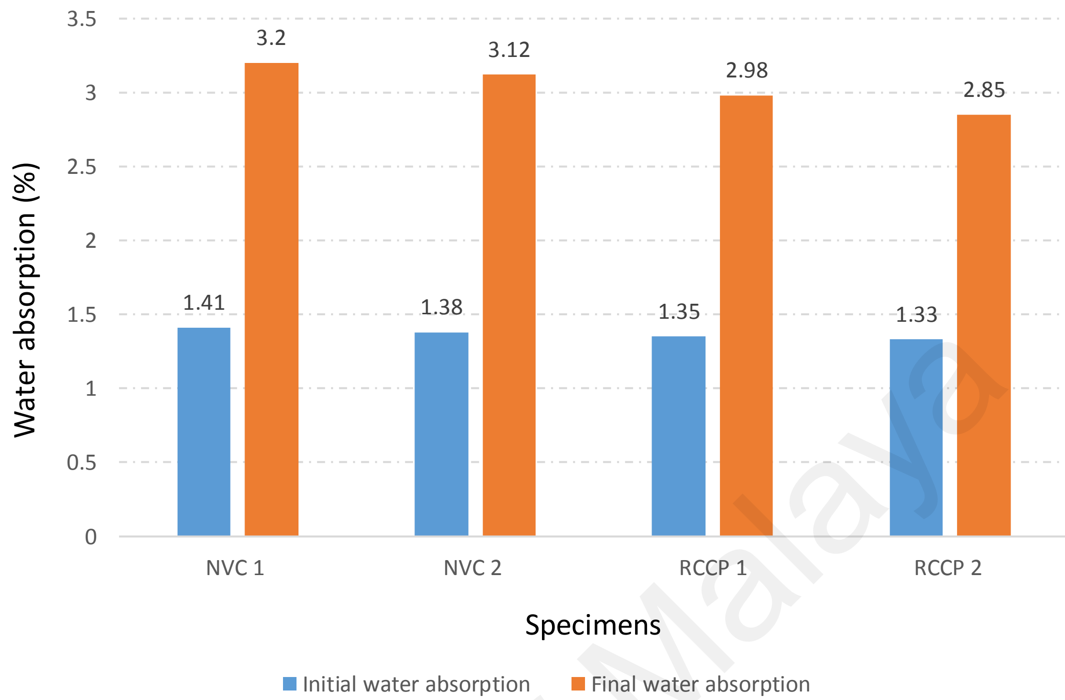


Figure 4.44: Initial and final water absorptions of the NVC and RCCP mixtures at 28-day

4.5.1.6 Porosity

The inverse relationship between porosity and strength of solids was reported by researchers (Tokyay, 2016). The porosity and pore size distribution of cement based materials significantly affect their mechanical and durability properties (Khatib et al., 2016). Porosity results of the RCCP and NVC mixtures are presented in Figure 4.45. It can be seen that the porosity results are in agreement with the results of water absorption test. The percent of porosity for RCCP1 and RCCP2 decreased approximately 10.8% and 10.4% in comparison with NVC1 and NVC2, respectively.

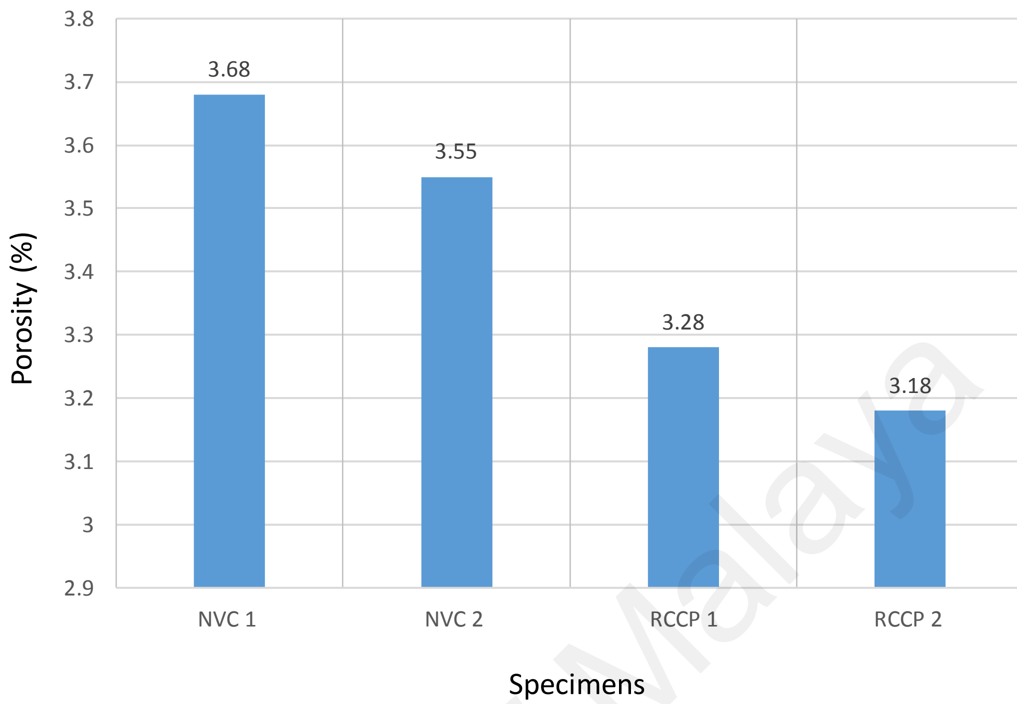


Figure 4.45: Porosity results for the NVC and RCCP mixtures at 28-day

4.5.1.7 Ultrasonic pulse velocity

The assessment of the ultrasonic pulse velocity (UPV) through concrete can give important information such as strength and elastic performance of concrete (De Brito & Saikia, 2012). The range of UPV qualitative rating varies from 3 to 4.5 Km/s (IS 13311). For excellent quality concrete, good quality concrete and medium quality concrete the UPV must be more than 4.5 Km/s, varying between 3.5-4.5 Km/s and between 3.0–3.5 Km/s, respectively. In this study, the UPV was about 4.21 and 4.33 Km/s for NVC1 and NVC2, respectively. Therefore, NVC mixtures were in the range of good quality concrete. However, this value was 4.61 and 4.77 Km/s for RCCP1 and RCCP2, respectively, that are in the range of excellent quality concrete. Figure 4.46 represents the strong correlation between UPV and 28-day compressive strength.

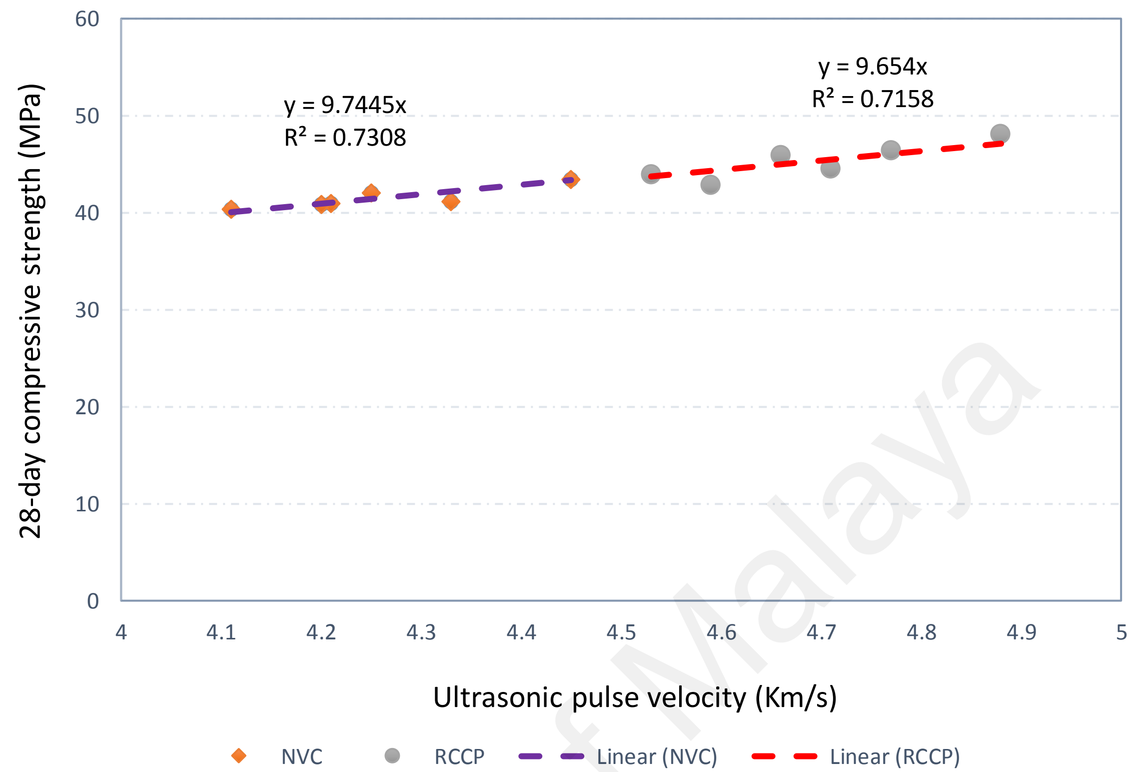


Figure 4.46: Relationship between UPV and 28-day compressive strength

4.5.1.8 Modulus of elasticity

The measured values of modulus of elasticity (MOE) results for the NVC and RCCP specimens are shown in Table 4.4. As shown, the result indicated that the MOE of the NVCs was between 27 and 29 GPa, however for RCCPs was between 32 and 35 GPa. The average MOE for the different RCCP mixes is reported about 30 GPa at 28-day (Gauthier & Marchand, 2005). The MOE of RCCP1 and RCCP2 were about 16.2% and 19% higher than MOE of NVC1 and NVC2, respectively. From the results it can also be observed that the behavior of modulus of elasticity is similar as that of compressive strengths.

The modulus of elasticity of concrete is known to be influenced by the cement paste, the aggregate's nature, the interfacial transition zone (ITZ) and the capacity of concrete (Neville,1995). According to European standard EC2 (1992-1-1:2008), the elastic deformations of concrete mostly depend on its composition, especially its aggregates. Aggregate volume content is one of the important factors affecting the properties of concrete (Yildirim & Sengul, 2011). Ouellet (1998) illustrated that the elastic modulus of the RCCP is influenced by the properties of the two phases in this mixture that are the hydrated cement paste and the aggregates. Therefore, it can be concluded that the higher binder content and porosity, and consequently lower total volume of aggregates in the NVCs in comparison with the RCCPs may be the reason behind the lower modulus of elasticity of the NVCs. In addition, the heavy compaction that applied on RCCP may be the other reason for higher MOE for RCCPs in comparison with NVCs.

To estimate the MOE of the RCCP, the models developed initially for the conventional concrete should be applied. ACI 318 developed a formula to estimate the modulus of elasticity of conventional concrete:

$$E_c = 4700\sqrt{f_c} \qquad \text{(Eq.4.2)}$$

where E_c is the modulus of elasticity [MPa], and fc is compressive strength of the concrete [MPa]

The measured and estimated values of MOE results for the NVC and RCCP specimens are compared in Table 4.7. A comparison of the estimated values provided by ACI 318 to the data obtained in this study showed that the measured values for NVC1 and NVC2 are about 7.2% and 6.9% lower than estimated values, however for RCCP1 and RCCP2 are about 3.8% and 5.6% higher than estimated values, respectively.

Table 4.4: The measured and estimated values of MOE for the NVC and RCCP specimens

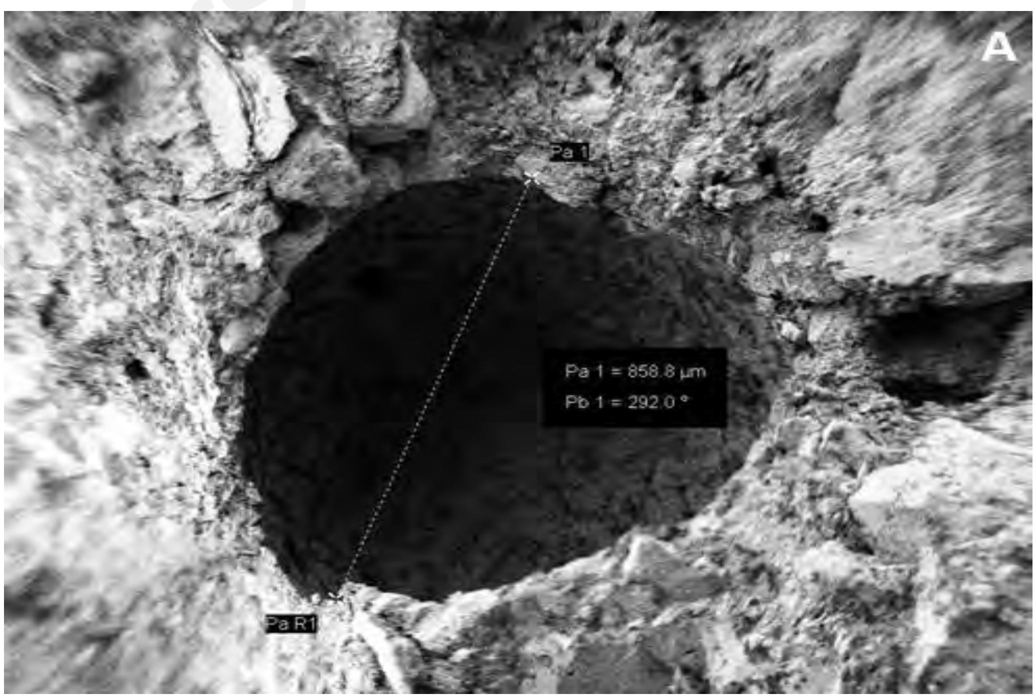
Mix	Measured MOE (GPa)	Estimated MOE by ACI 318 (GPa)
NVC1	27.9	29.9
NVC2	28.8	30.8
RCCP1	32.4	31.14
RCCP2	34.3	32.37

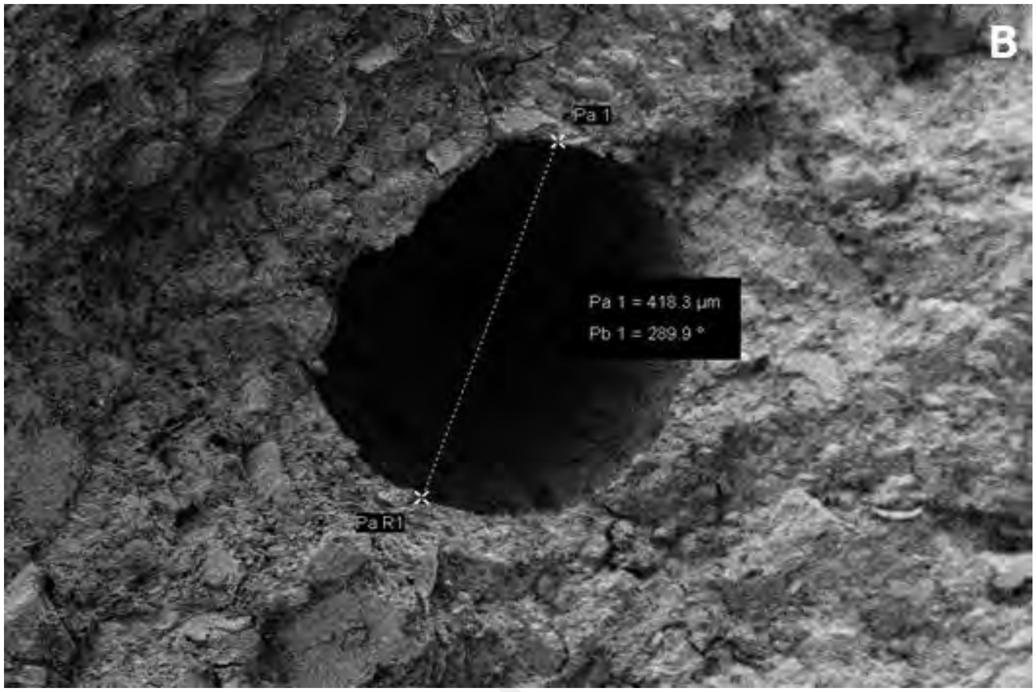
The analysis of the behaviour of the materials under the action of the loads is usually, presented by the relation between the deformation and the force which causes it (Zdiri et al., 2007). The modulus of elasticity expresses the ratio between the applied stress and strain in the linear region. From the results can be concluded that the NVC specimens reached their breaking points at lower stress, without much strain softening in comparison with RCCP specimens.

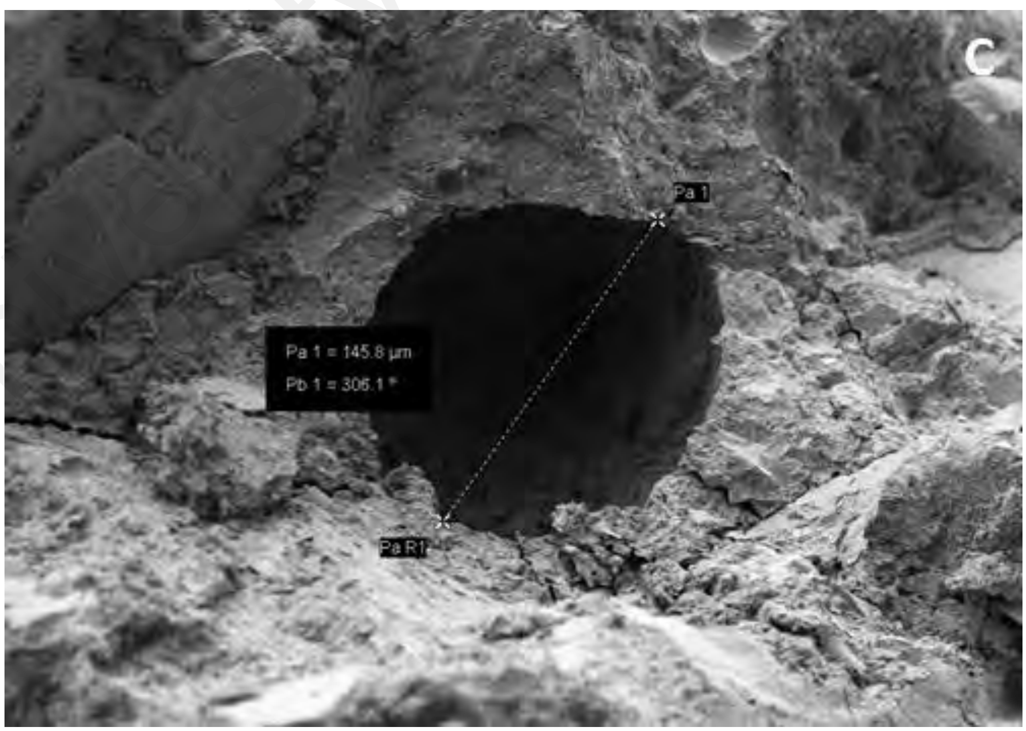
4.5.1.9 Field Emission Scanning Electron Microscope Test

The microstructural configurations for different NVC and RCCP samples were investigated using field emission scanning electron microscope (FESEM) as shown in Figure 4.47. The FESEM test was used to detect entrapped air voids and compaction voids in NVC and RCCP specimens. The durability of concrete is depended on the characteristics of its pore structure (Schutter & Audenaert, 2004) and it is obtained when pore structure gets tight and highly impermeable (Kolyvas, 2007). The entrapped air voids affect the strength of concrete adversely (Mehta, 1986). Generally, compaction voids are irregular in shape. However, the air voids are generally spherical in shape (Mehta & Monteiro, 2006).

The FESEM test results has shown that 1) There was no compaction voids observed in NVC and RCCP specimens. An interconnected network could be formed due to the high number of compaction voids which seriously jeopardizes durability of concrete and can affect its freeze-thaw resistance (Khayat & Libre, 2014). Generally, the compaction voids are irregular and large in shape. They are formed due to improper compaction of concrete during casting 2) the maximum air voids size that found in RCCP mixture was about 192 μm, however, it was about 858 μm in NVC mixture which makes the microstructure of the paste more porous and results in lower strength. During concrete mixing usually a little amount of air gets trapped in the cement paste. Entrapped air voids are generally spherical in shape and may be as large as 3 mm (Mehta & Monteiro, 2006). The entrapped air voids affect the strength of concrete adversely (Mehta,1986).




B
Pa 1
Pa 1 = 418.3 µm
Pb 1 = 289.9 °
Pa R1


C
Pa 1
Pa 1 = 145.8 µm
Pb 1 = 306.1 °
Pa R1

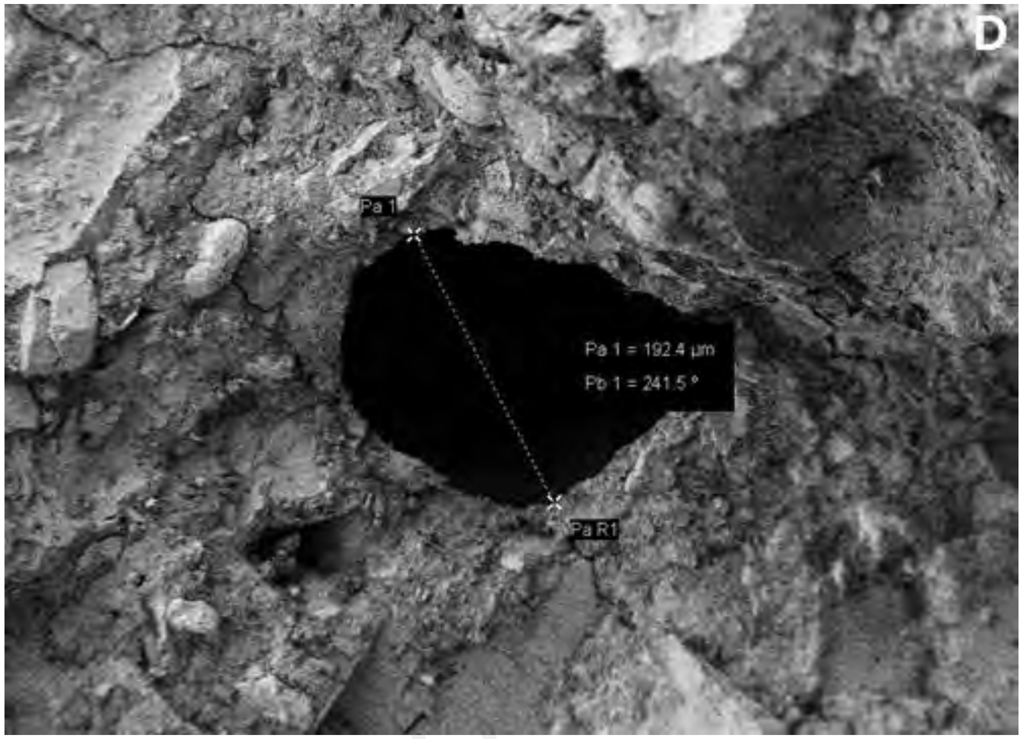


Figure 4.47: The maximum void size in the paste of NVC and RCCP specimens. A: NVC1; B: NVC2; C: RCCP1; D: RCCP2

4.5.1.10 Thermal conductivity Test

Thermal properties of pavement material have a vital role on forming Urban Heat Island (UHI) (Mirzanamadi et al., 2018). The heat transfer in concrete at usual operating temperatures is mainly by conduction. Thermal conductivity is a property of material, which demonstrated its capability in heat conduction (Tong, 2011; Zhang et al., 2015). Table 4.5 summarized the average thermal conductivity and oven dried density of different samples.

Sengul et al. (2011) revealed that there is a significant relationship between unit weight of concrete and the value of thermal conductivity. Figure 4.48 shows the relationship between thermal conductivity and density of specimens at oven-dried conditions.

Table 4.5: Average thermal conductivity and density of samples at the age of 28 days

Mix	Density (kg/m^3)	Thermal conductivity (W/m.°K)
NVC1	2287	2.44
NVC2	2308	2.47
RCCP1	2339	2.52
RCCP2	2374	2.69

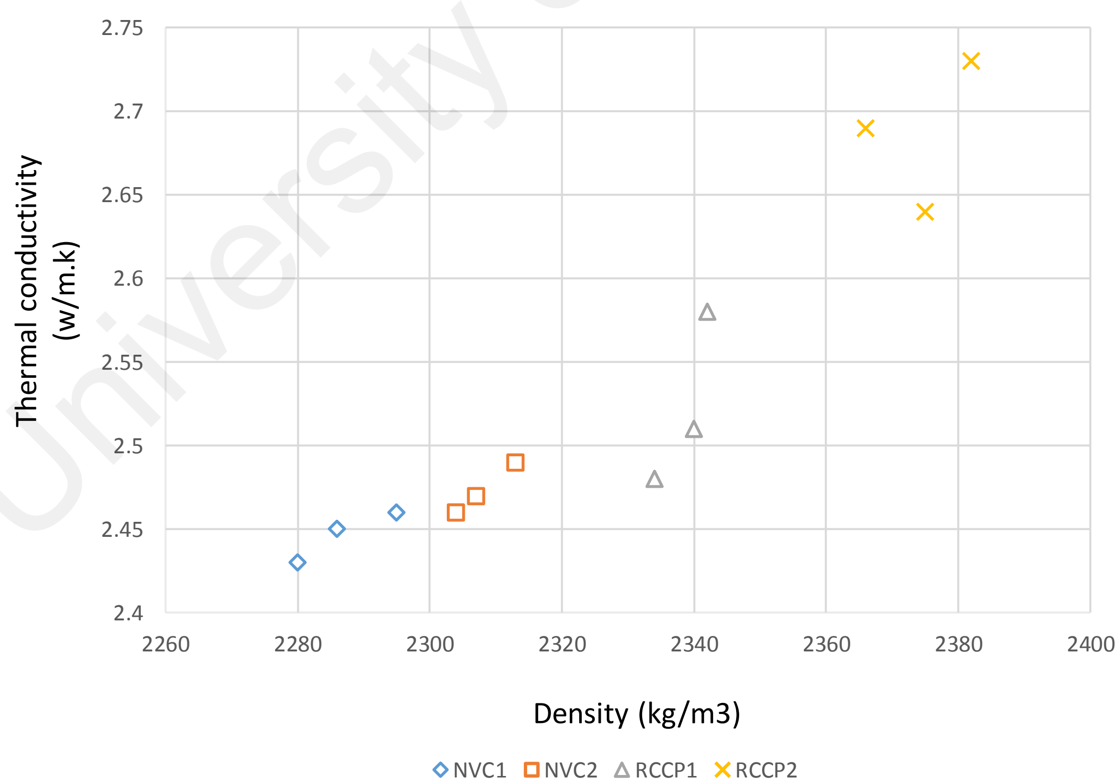


Figure 4.48: The relation between thermal conductivity and density

The average thermal conductivity of NVC and RCCP samples are about 2.45 W/m.°K and 2.60 W/m.°K, respectively. Based on literature the thermal conductivity of lightweight concrete is in the range of 0.2 to 1.9 W/m.°K, while it is up to 3.3 W/m.°K for normal weight concrete (Newman & Owens, 2003; Real et al., 2016; Holm & Bremner, 2000; Yun et al., 2013) . The results show that the k-value of both NVC and RCCP is in the range of normal weight concrete. However, the RCCP has more capability in heat transfer and preparing the lower surface temperature in comparison to NVC. This capability is due to its dens structure compared to the NVC. Eq.4.3 and Eq.4.4 could be used to predict the thermal conductivity value of NVC and RCCP, respectively.

$$k = 0.0015\rho - 0.9125 \qquad (R^2 = 0.88) \qquad \text{(Eq.4.3)}$$

$$k = 0.0045\rho - 8.0712 \qquad (R^2 = 0.86) \qquad \text{(Eq.4.4)}$$

Where K is thermal conductivity (W/m.°K) and ρ is density (Kg/m^3).

4.6. The effect of superplasticizer admixture on the fresh and hardened properties of roller-compacted concrete pavement

4.6.1 Results and analysis

4.6.1.1 Fresh properties

Table 4.6 shows the fresh properties of all RCCPs. Sufficient workability for all RCCP mixes was observed. Based on the visual inspection, no segregation or bleeding was observed for all the mixes during mixing, placing and compaction. According to the test results, Vebe time decreased with the use of superplasticizer. The Vebe time for RCCPs containing 12% and 15% cement content was 37 s and 30 s, respectively. The use of 0.25% and 0.5% superplasticizer for RCCPs containing 12% cement decreased the Vebe time by 11% and 22%, respectively. Also, the use of 0.25% and 0.5% superplasticizer for RCCPs containing 15% cement reduced the Vebe time by 17% and 27%, respectively. It shows the positive effect of adding superplasticizer was more significant for RCCPs containing 15% cement content. Based on ACI 325 the Vebe time is limited to 30-40 s for producing RCCP. On the other hand, increasing the cement content from 12% to 15% decreased the Vebe time by 18%. Vahedifard et al. (2010) reported that increasing the cement content in RCCP from 12% to 15% decreased the Vebe time by 10%.

The oven dry density for RCCPs containing 12% cement content was in the range of 2318-2347 Kg/m^3. In addition, this value ranged from 2377 to 2386 kg/m^3 for RCCPs containing 15% cement content. It has reported that RCCP has the density range from 2340 to 2510 kg/m^3 (Delatte, 2014). The test results show that increasing the cement content from 12% to 15% and the use of superplasticizer in RCCP may increase the density. This could be because of easy compaction due to increasing cement content and adding superplasticizer which can provide higher pack density and denser structure. Naik et al. was found that silica fume with superplasticizer increased the density of RCCP (Naik et al., 2001).

Table 4.6: Fresh properties for RCCP specimens

Mix	Vebe Time (S)	Oven dry density (Kg/m^3)
A-12	37	2318
A-12-0.25	33	2333
A-12-0.50	29	2347
B-15	30	2377
B-15-0.25	25	2386
B-15-0.50	22	2386

4.6.1.2 Compressive strength

Compressive strength is the property most often used to describe the quality of concrete in practice (Wiegrink., 1996). The standard deviation for the compressive strength results were 5-9%. The compressive strength was determined at 7 and 28-day age and the results are presented in Figure 4.49 and figure 4.50. The compressive strength of RCCPs with 12% cement content at 7 and 28 days was 27.3–31.8 MPa and 37.2–40.9 MPa, respectively. For RCCPs with 15% cement content the compressive strengths were in the range of 32.3–37.9 MPa and 41.3–46.9 MPa, respectively. Portland Cement Association (PCA) noted that the compressive strength of RCCP typically ranges from 28 to 41 MPa.

The 7-day compressive strength for RCCPs containing 12% and 15% cement, increased by 4% and 7% when 0.25% superplasticizer was added, also these values increased by 15% and 17% when 0.50% superplasticizer was used, respectively. In addition, the use of 0.25% and 0.50% superplasticizer increased the 28-day compressive strength about 2% and 9% for RCCPs containing 12% cement and 4% and 14% for RCCPs with 15% cement content. The results indicate that the impact of superplasticizer on the compressive strength gain is considerable, especially for RCCPs with 15% cement. The increase in compressive strength with the addition of superplasticizer may due to proper distribution and dispersion of paste which leads to better compaction and reduction in voids in the hardened RCCP. Superplasticizers improve fluidity of concrete by dispersing cement particles present in the paste (Lei & Plank, 2012). The use of superplasticizer will increase compressive strength by enhancing the effectiveness of compaction to produce denser concrete (Alsadey, 2015).

On the other hand, the compressive strengths of RCCPs containing 15% cement at 7-day was about 18%, 22% and 19% and at 28-day 11%, 13% and 15% higher than the strength of its counterpart equivalent concretes made with 12% cement content. Therefore, the role of cement increment on the compressive strength gain was more considerable at early ages. It should be noted that the compressive strength of RCCPs with 12% cement and 0.5% superplasticizer was comparable with RCCPs containing 15% cement without superplasticizer at 7-day and 28-day age. So, the compressive strength of RCCP could be increased by adding 0.5% superplasticizer and without cement increment which leads to reducing risk of drying shrinkage. In general, increasing cement content results in drying shrinkage increment (Mehta,1986).

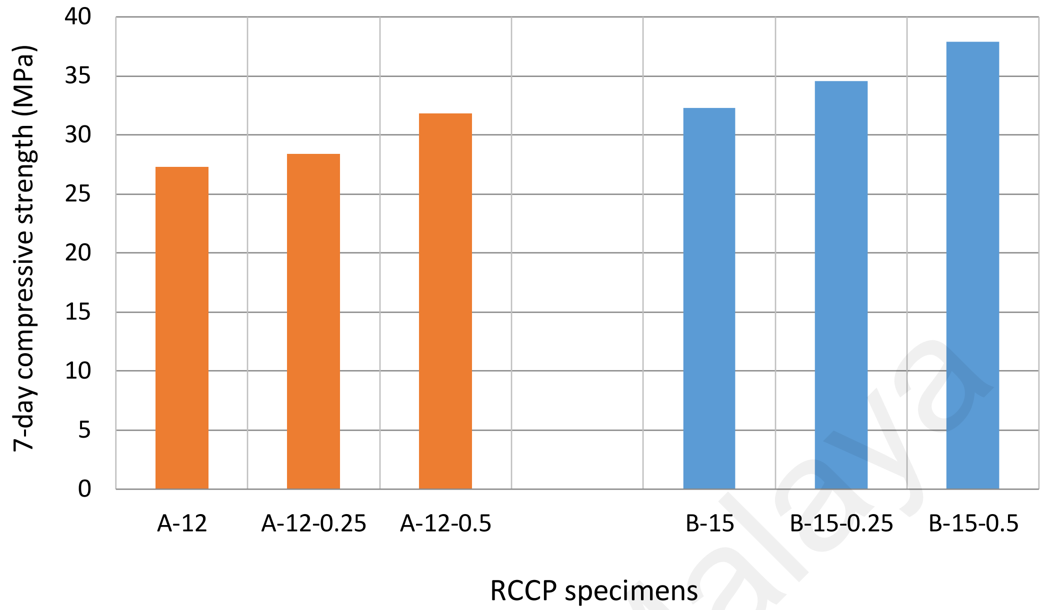


Figure 4.49: Compressive strength for RCCP mixtures at 7-day

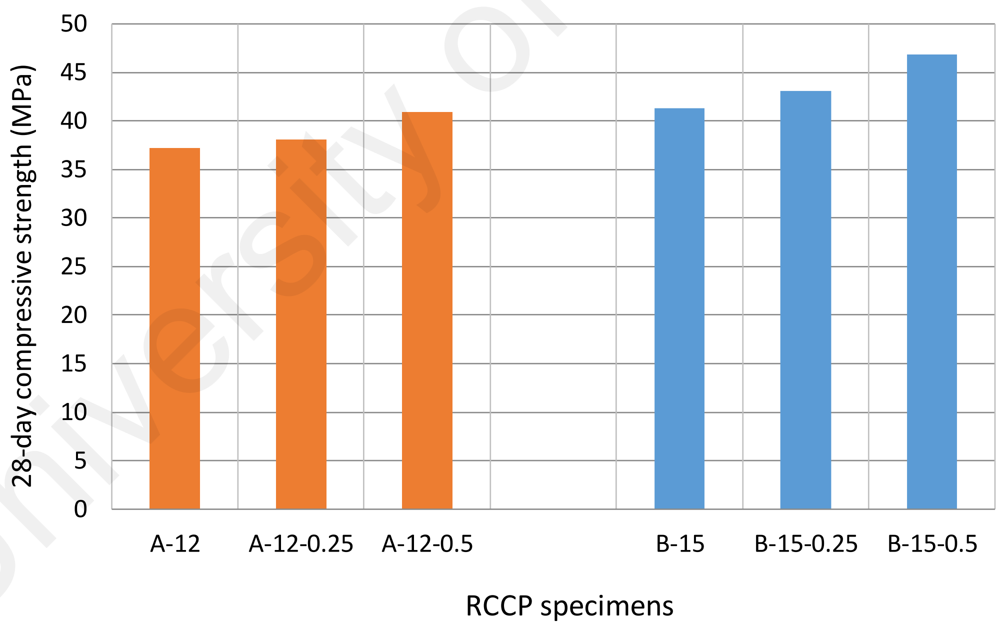


Figure 4.50: Compressive strength for RCCP mixtures at 28-day

4.6.1.3 Splitting tensile strength

The splitting tensile strength results of the RCCP mixes at 7 days and 28 days are shown in Figure 4.51 and Figure 4.52. The standard deviation for the splitting tensile strength results were 4-7%. The 28-day splitting tensile strength of RCCPs with 12% and 15% cement was in the range of 3.9-4.6 MPa and 4.6-5.3 MPa, respectively. The British Department of Transport (Calverley, 1977) specified that a concrete to be used in road construction must have at least 1.8 MPa splitting tensile strength at 28 days.

The splitting tensile strength shows the same trend with compressive strength, showing the higher values with the use of 0.25% and 0.50% superplasticizer at early ages and 28days. The use of 0.25% and 0.50% superplasticizer increased the splitting tensile strength about 10% and 17% for RCCPs with 12% cement and about 10% and 21% for RCCPs with 15% cement content at 7-day age. Also, a similar enhancement at 28-day age about 5% and 16% for RCCPs with 12% cement and 5% and 17% for RCCPs with 15% cement was observed. The test results show 1) improvement effect of superplasticizer is more considerable for RCCPs with 15% cement content 2) improvement effectiveness of superplasticizer is more significant for splitting tensile strength in comparison with compressive strength at early ages and 28 days.

The splitting tensile strength of RCCPs containing 15% cement at 7-day was about 17%, 16% and 21% and at 28-day 15%, 17% and 16% higher than the strength of its counterpart equivalent concretes made with 12% cement content. From the results can be concluded that the increment of splitting tensile strength due to the use of 0.50% superplasticizer for both cement contents was comparable or higher than increasing cement from 12%to 15% at 7-day and 28-day ages.

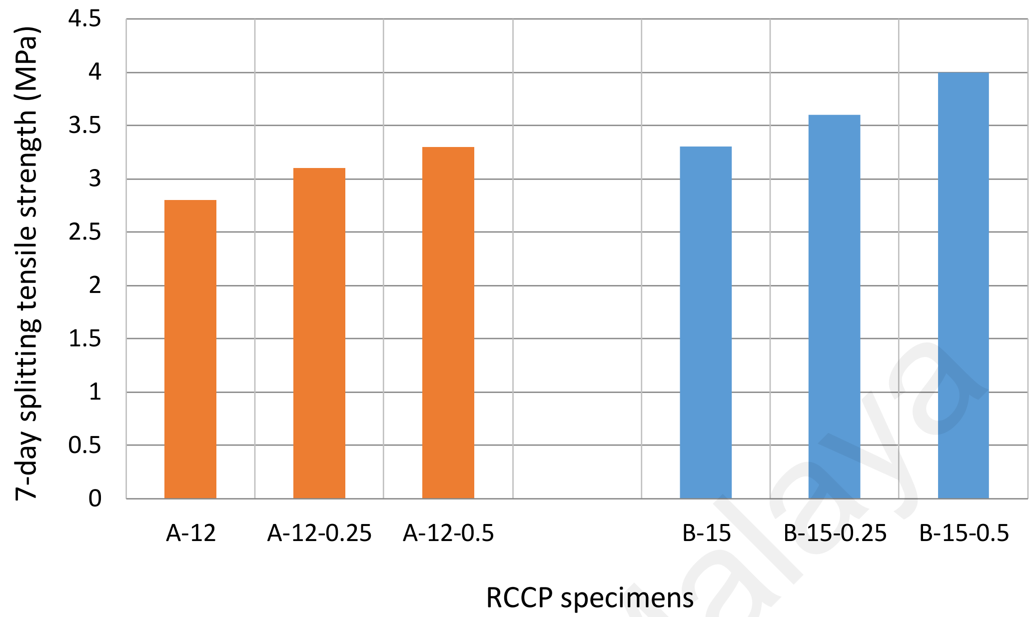


Figure 4.51: Splitting tensile strength for RCCP mixtures at 7-day

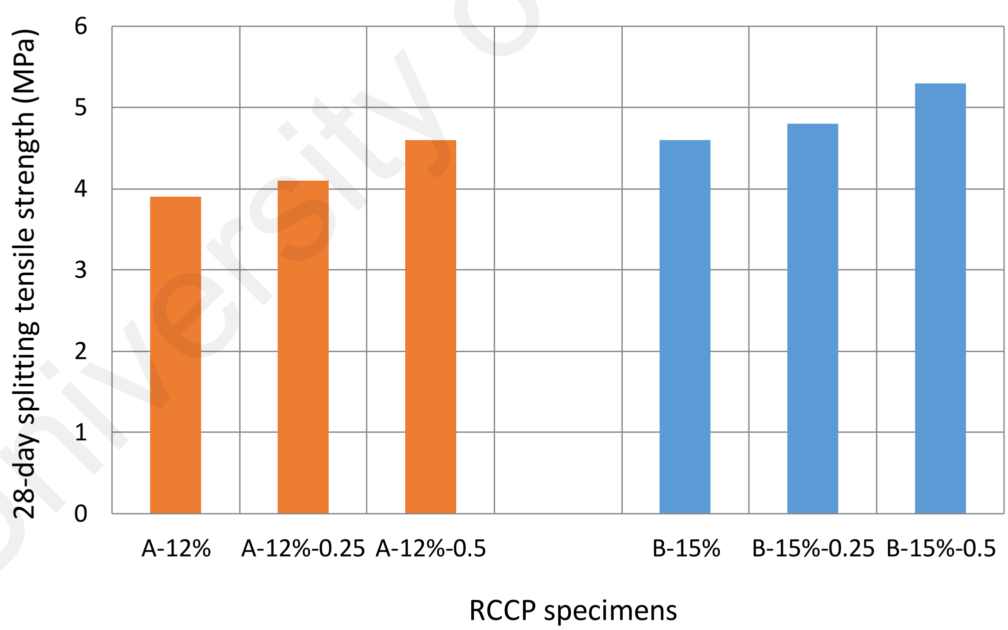


Figure 4.52: Splitting tensile strength for RCCP mixtures at 28-day

4.6.1.4 Flexural tensile strength

Figure 4.53 and Figure 4.54 show the flexural tensile strength results. The standard deviation for the flexural tensile strength results were found between 3-6%. Similar enhancement in the flexural tensile strength was observed with the use of superplasticizer in both cement content at 7-day and 28-day ages. With the use of 0.25% and 0.50% superplasticizer, 7-day flexural tensile strength increased about 5% and 10% for RCCPs containing 12% cement content and about 7% and 24% for RCCPs with 15% cement content. In addition, this value increased about 4% and 10% for RCCPs with 12% cement and 5% and 11% for RCCPs with 15% cement at 28 days. Flexural tensile strength is directly related to the unit weight and compressive strength of the concrete mixture (Khayat & Libre, 2014). It is considerable that the increment of flexural tensile strength due to the use of 0.50% superplasticizer for both cement contents was comparable or higher than increasing cement from 12%to 15% at early ages and 28 days.

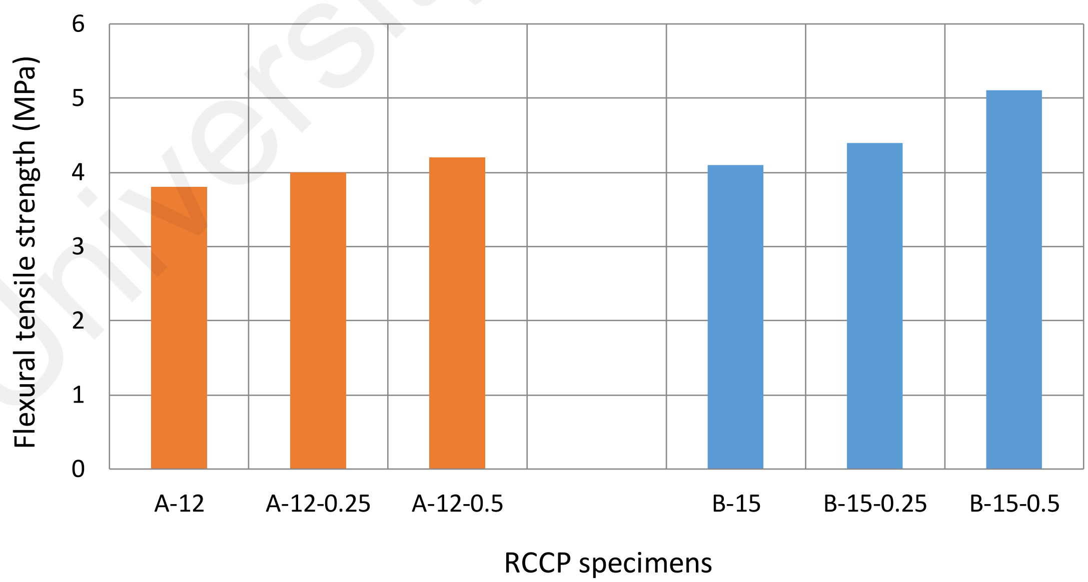


Figure 4.53: Flexural tensile strength for RCCP mixtures

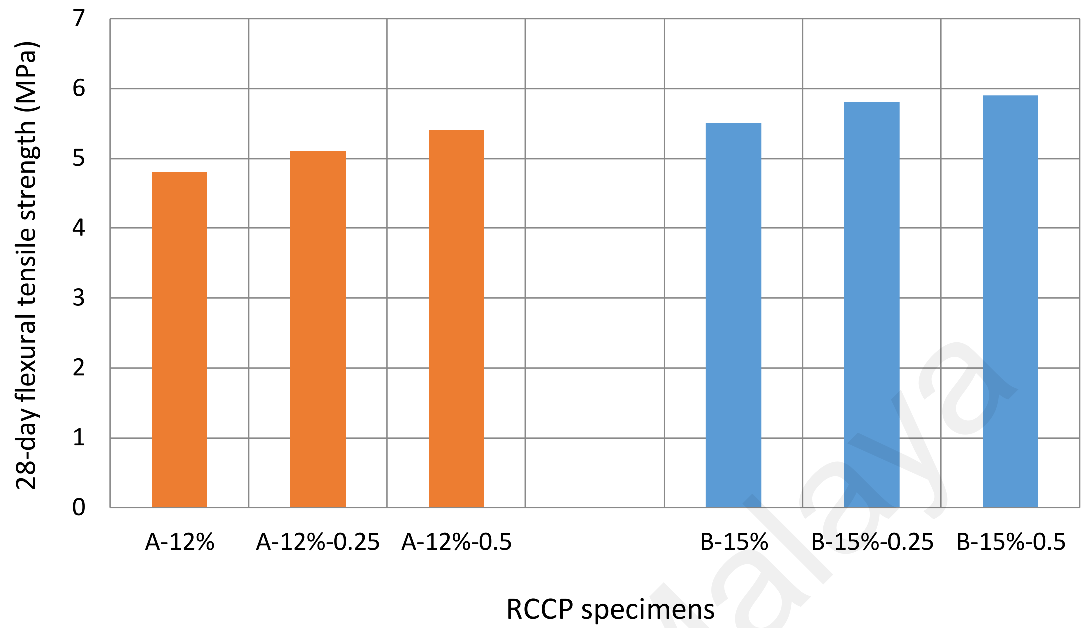


Figure 4.54: Flexural tensile strength for RCCP mixtures

4.6.1.5 Water absorption and porosity

The durability of concrete can be evaluated by a number of properties such as water absorption and porosity (Mohammadi, 2013). The results for initial water absorption after 30 min, final water absorption after 72 h and porosity are demonstrated in Figure 4.55. As can be seen the initial surface water absorption of all RCCP mixtures showed values lower than 3%. In addition, the final water absorption for all RCCPs with 15% cement and RCCP containing 12% cement with 0.50% superplasticizer was lower than 3%. However, it was 3.2% and 3.1% for A-12 and A-12-0.25 mixtures, respectively.

The results revealed that initial, final water absorption and porosity values are highly affected by the use of superplasticizer. The final water absorption and porosity values for RCCPs containing 12% cement decreased about 3% and 5% with the use of 0.25% superplasticizer and 7% and 8% with the use of 0.50% superplasticizer, respectively. Also, the use of 0.25% superplasticizer for RCCPs containing 15% cement decreased the final water absorption and porosity about 2% and 3% and the use of 0.50% superplasticizer decreased about 8% and 4%. Decreasing in the water-cement ratio, increasing in the curing time, and increasing in the degree of consolidation result in decrease in water absorption and porosity values (Mehta & Monteiro, 2006). The inverse relationship between porosity and strength of solids was reported by researchers (Tokyay, 2016). The porosity and pore size distribution of cement based materials significantly affect their mechanical and durability properties (Khatib et al., 2016).

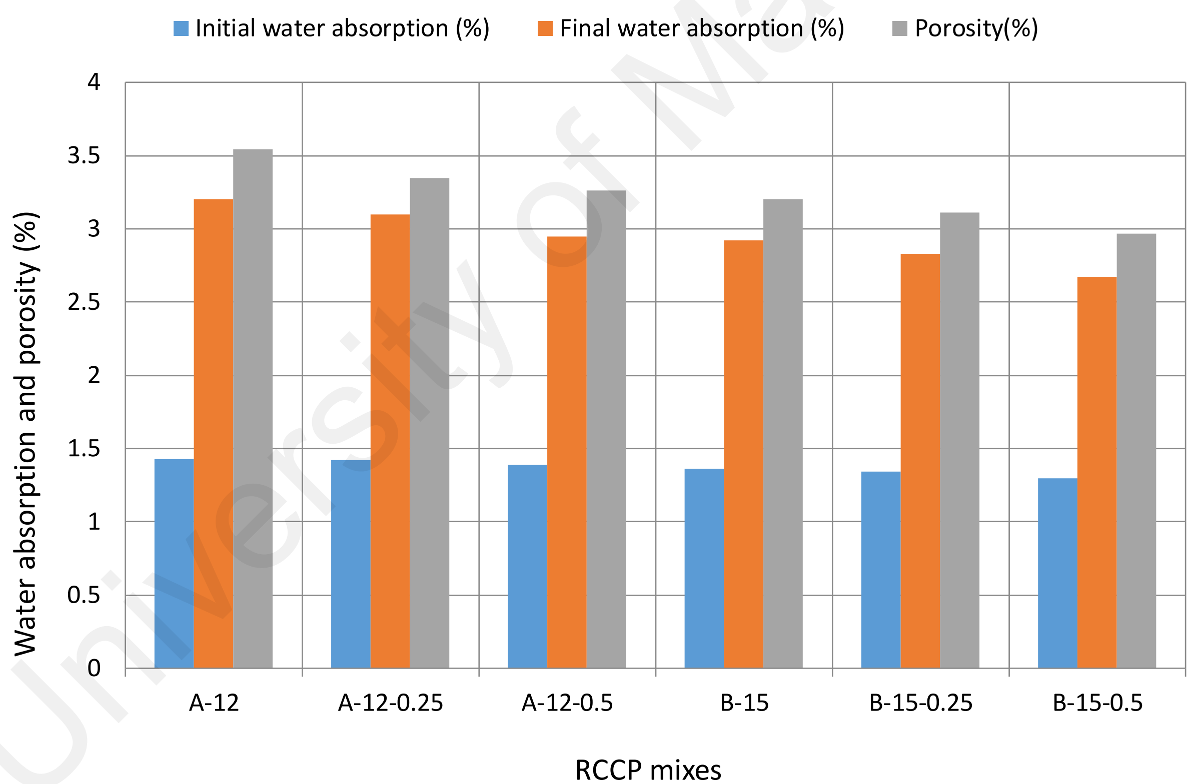


Figure 4.55: Initial and final water absorptions and porosity values of the RCCP mixtures at 28-day

4.6.1.6 Ultrasonic pulse velocity

The assessment of the ultrasonic pulse velocity (UPV) through concrete can give important information such as strength and elastic performance of concrete (De Brito & Saikia, 2012). The range of UPV qualitative rating varies from 3 to 4.5 Km/s (IS 13311, 1992). In this study, the UPV values for all RCCPs except A-12 and A-12-0.25 were more than 4.5 Km/s. Figure 4.56 shows UPV test results for RCCPs containing 12% and 15% cement. The results revealed that the UPV values for RCCPs with 12% and 15% cement increased with the use of superplasticizer. Also, cement increment from 12% to 15% significantly increased the UPV values. Figure 4.57 represents the strong correlation between UPV and 28-day compressive strength.

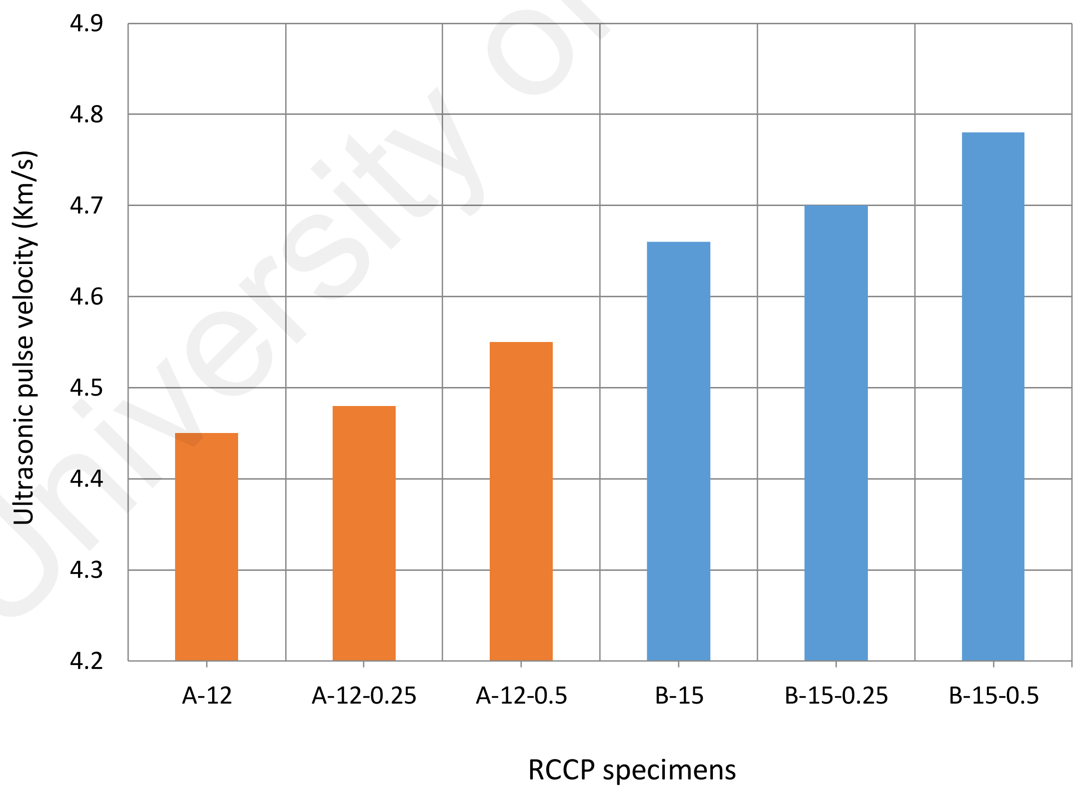


Figure 4.56: UPV test results for RCCP mixtures

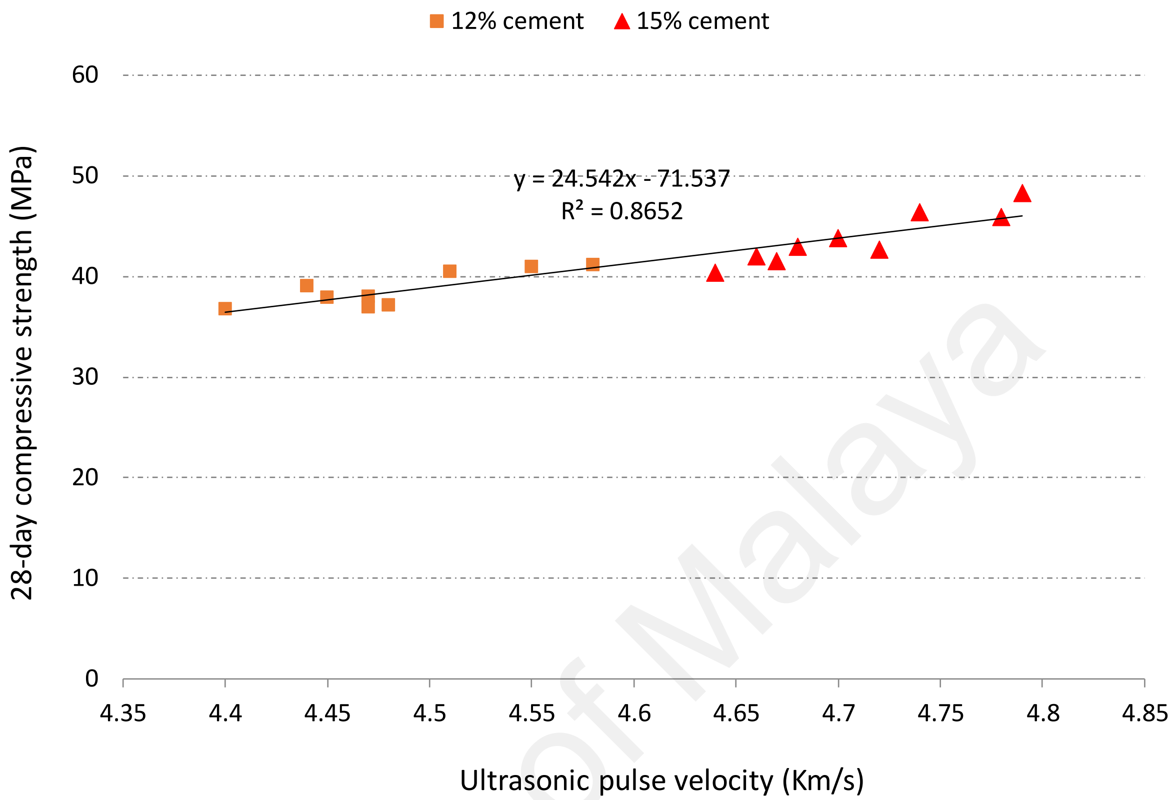
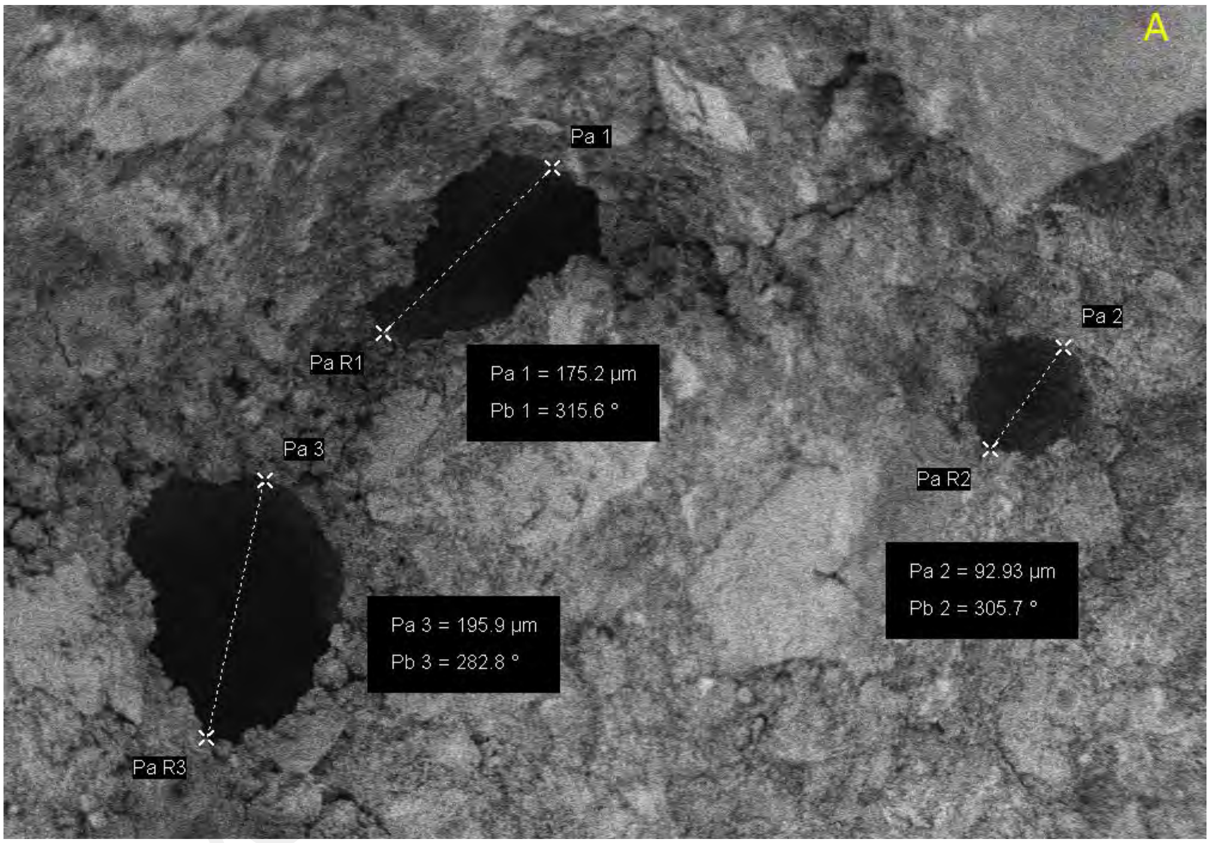
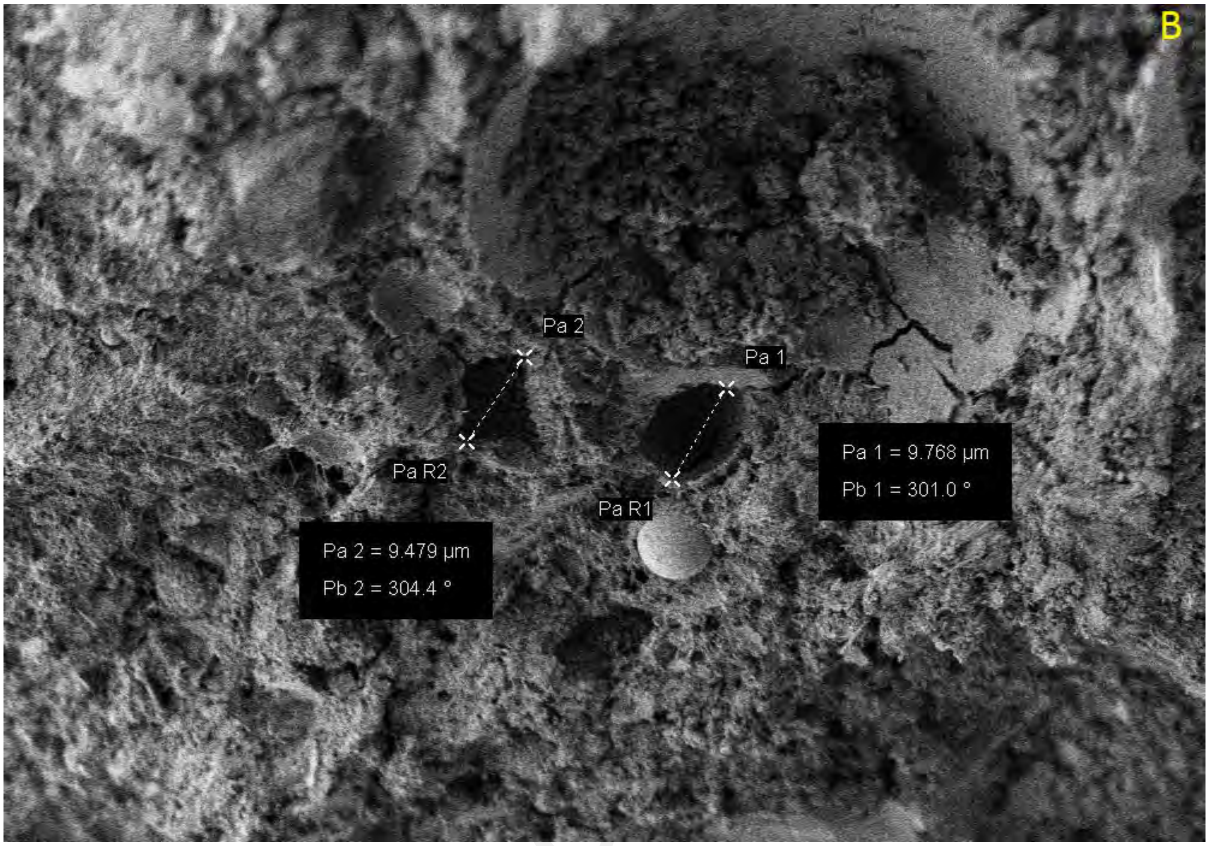


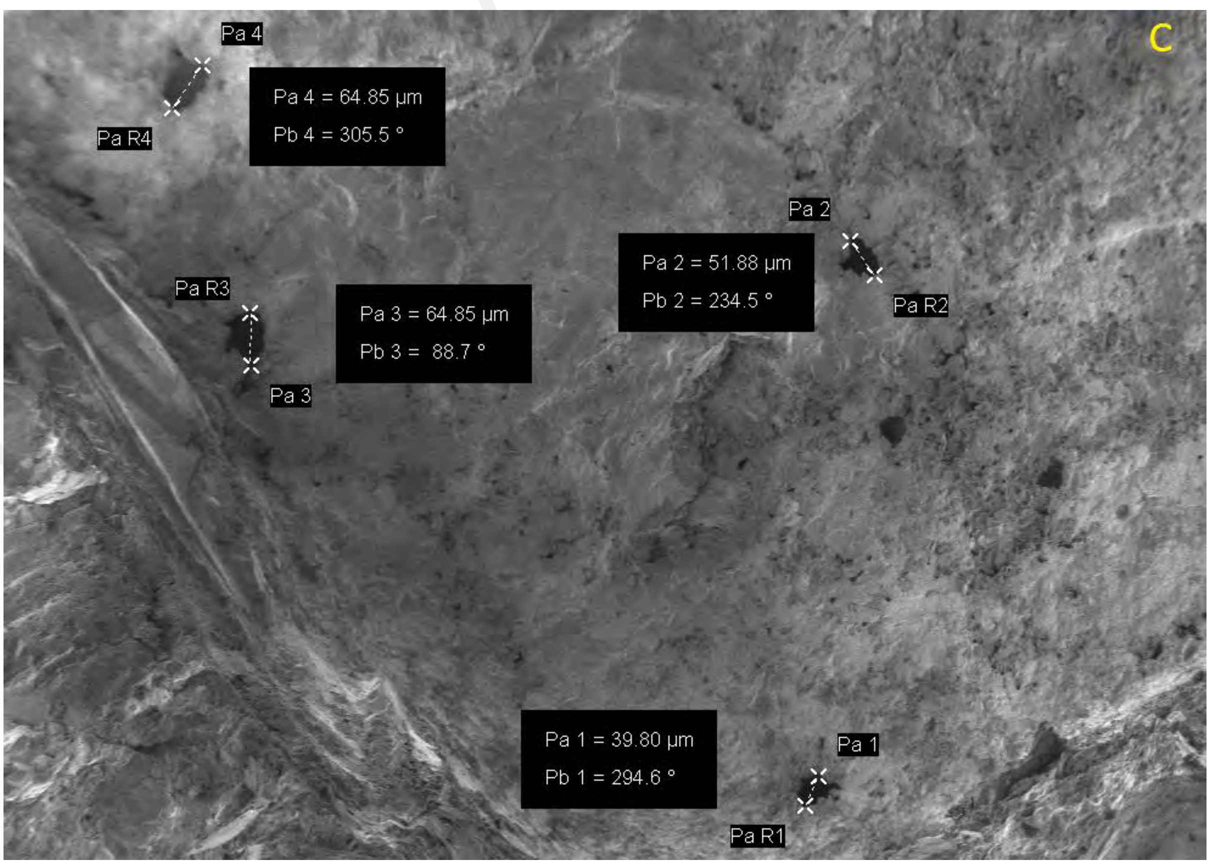
Figure 4.57: Relationship between UPV test and 28-day compressive strength

4.6.1.7 Field Emission Scanning Electron Microscope Test

The microstructural configurations for different RCCP samples were investigated using field emission scanning electron microscope (FESEM) as shown in Figure 4.58. The FESEM test was used to detect denser RCCP matrix. The durability of concrete is depended on the characteristics of its pore structure (De Schutter & Audenaert, 2004). and it is obtained when pore structure gets tight and highly impermeable (Kolyvas, 2007). The existing voids in paste affect the strength of concrete adversely (Mohammadi, 2013). Generally, compaction voids are irregular in shape. However, the air voids are generally spherical in shape (Mehta & Monteiro, 2006). The FESEM test results has shown that 1) there was no compaction voids in all RCCP specimens 2) in the absence of superplasticizer the maximum void size increased in RCCP specimens which makes the microstructure of the cement matrix more porous thus leading to drop in the strength. However, the decrease in void size with the addition of superplasticizer is due to increased paste distribution and dispersion resulting in proper compaction, and denser RCCPs.




B
Pa 2
Pa 1
Pa R2
Pa R1
Pa 1 = 9.768 µm
Pb 1 = 301.0 °
Pa 2 = 9.479 µm
Pb 2 = 304.4 °


C
Pa 4
Pa R4
Pa 4 = 64.85 µm
Pb 4 = 305.5 °
Pa 2
Pa 2 = 51.88 µm
Pb 2 = 234.5 °
Pa R2
Pa R3
Pa 3 = 64.85 µm
Pb 3 = 88.7 °
Pa 3
Pa 1 = 39.80 µm
Pb 1 = 294.6 °
Pa 1
Pa R1

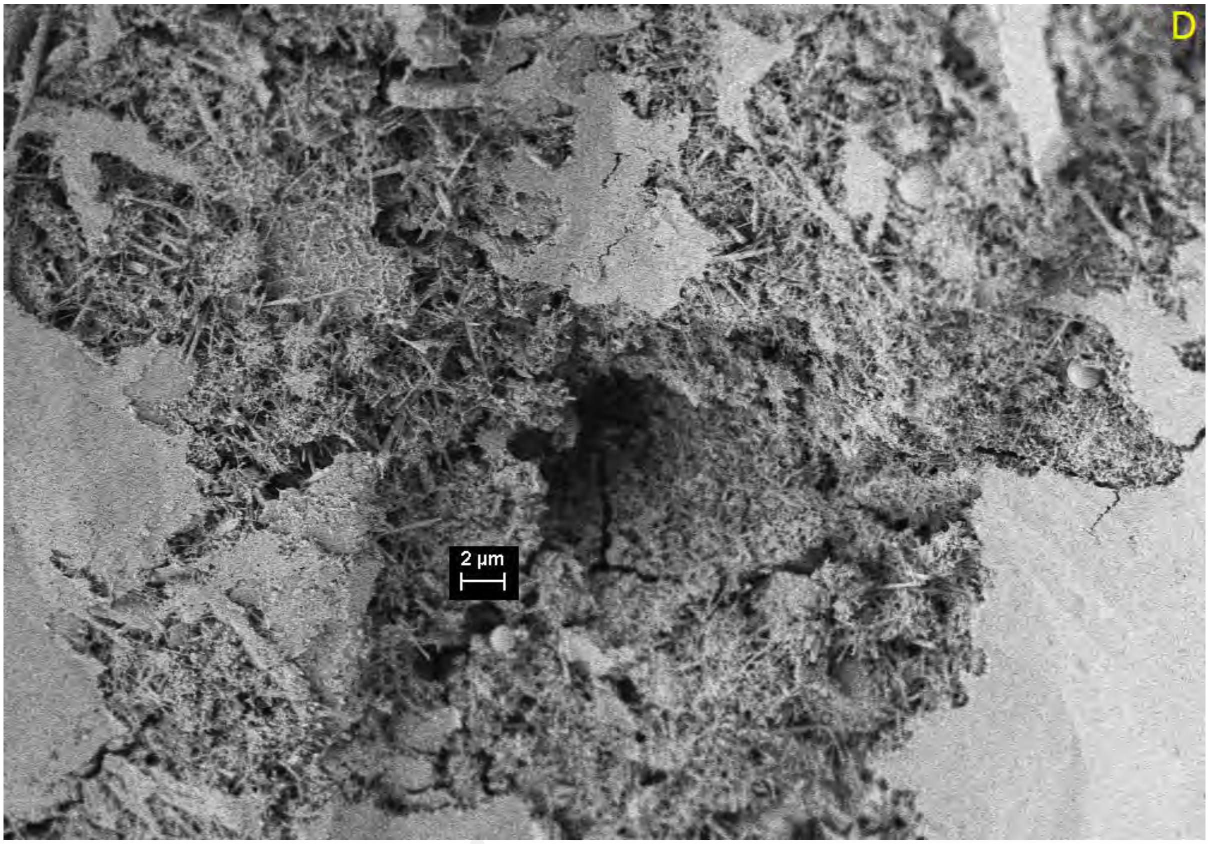


Figure 4.58: The effect of using superplasticizer on the void size in the paste of RCCPs. A: A-12; B: A-12-0.50; C: B-15; D: B-15-0.50

4.6.1.8 Thermal conductivity Test

Conduction heat transfer in solids is a mixture of vibrations of the molecules and energy transport by free electrons (Bhattacharjee & Krishnamoorthy, 2004). Thermal conductivity (k-value) is a property of material, which demonstrated its capability in heat conduction (Tong, 2011; Zhang et al., 2015). Thermal conductivity is the most important thermal properties that affect the heat transfer by conduction through concrete (Bhattacharjee & Krishnamoorthy, 2004). Thermal properties of pavement material have a vital role on forming Urban Heat Island (UHI) (Mirzanamadi et al., 2018). Materials with higher thermal conductivity are capable to transfer heat from the surface in a higher rate compared to the substance with low thermal conductivity. Concrete is a heterogeneous and permeable solid material. The heat transfer in concrete material, at normal operating temperatures, is mainly by conduction. Every concrete mixture has a unique k-value based on its mixture proportion. Table 4.7 summarized the k-value range of different RCCPs.

Table 4.7: Thermal conductivity of samples at the age of 28 days

Sample ID	Thermal conductivity (W/m.°K)
A-12	2.1-2.26
A-12-0.25	2.31-2.55
A-12-0.5	2.53-2.68
B-15	2.51-2.87
B-15-0.25	2.78-2.89
B-15-0.5	2.84-2.93

The results indicate that the k-value of samples containing superplasticizer are more than control samples. The void inside the concrete has an important effect on mechanical and thermal properties of concrete (Chung et al., 2016). Therefore, this gradual increment in the k-value of samples can be attributed to the reduction of porosity and preparing denser cement paste due to adding superplasticizer. The achieved results of k-value in this study is in the range of reported k-value for concrete by other researchers. Based on available literature the thermal conductivity of lightweight concrete is in the range of 0.2 to 1.9 W/m.°K while it has been reported up to 3.3 W/m.°K for normal weight concrete (NWC) (Newman & Owens, 2003; Real et al., 2016; Holm & Bremner, 200; Yun et al., 2013).

4.7. Engineering properties of roller-compacted lightweight concrete pavement

4.7.1 Results and analysis

4.7.1.1 Vebe Time

Table 3.9 shows the Vebe time for RCCPs. Based on the visual observation there was sufficient workability for all mixes. The Vebe time for RCCPs containing 12% and 15% cement was in the range of 26-34 sec and 20-30 sec, respectively. The results showed that as the percentage of LECA increased, the workability of RCCP increased for fixed water to cement ratio. This may be due to the round shape of LECA aggregates compared to the normal weight aggregates. Other studies reported more workable concrete mixtures by substitution normal weight coarse aggregate with LECA (Shebannavar et al., 2015; Youm et al., 2016; Bogas et al., 2014).

Incorporation of 25, 50, 75 and 100% LECA in RCCP containing 12% cement, decreased Vebe time by about 3, 9, 15 and 23%, and also for RCCP containing 15% cement the Vebe time reduced by 7, 13, 23 and 33%, respectively. In addition, increasing cement from 12% to 15% resulted in decreased Vebe time for RCCPs containing 0, 25,50,75 and 100% by 12, 15, 16, 20 and 23%, respectively. Vahedifard et al (2010) showed that the cement increment from 12% to 15% in RCCP can decrease the Vebe time by 10 percent. Figure 4.59 and Figure 4.60 illustrate finished surface of RCCPs containing 100% LECA after the Vebe test and slump test for both cement contents.

(a) (b)

Figure 4.59: Surface texture after Vebe time test. (a) RCCP containing 12% cement (b) RCCP containing 15% cement

(a) (b)

Figure 4.60: Slump test. (a) RCCP containing 12% cement (b) RCCP containing 15% cement

4.7.1.2 Density

Table 3.9 shows decrease in density by incorporation of LECA into RCCP mixes. This reduction increased with the increase the amount of LECA. The replacement of 25, 50, 75 and 100% LECA by volume as normal weight coarse aggregate in RCCPs containing 12% cement decreased the density by 8, 15, 20 and 24% and also for RCCPs containing 15% cement the density decreased by 7, 13, 18 and 23%, respectively. It should be noted this decrease was more considerable for RCCPs with 12% cement.

The oven dry density of LWAC should not be more than 2000 kg/m^3, but can be as low as 800 kg/m^3 depending on its materials (Shafigh et al., 2018). However, the oven dry density of a semi-lightweight concrete could be between 1840 kg/m3 and 2240 kg/m3 (Adel et al., 2014). Therefore, RCCPs with 12% and 15% cement contents containing 75 and 100% LECA can be considered as a lightweight aggregate concrete, while RCCPs with 12% cement content containing 25 and 50% LECA and RCCPs with 15% cement content containing 25 and 50% LECA can be categorized as a semi-lightweight concrete. The density of the RCCP ranged from 2340 to 2510 kg/m3 that the corresponding compressive strength ranged from 20 to 55 MPa (Delatte, 2014).

4.7.1.3 Compressive strength

Compressive strength results of the various mixes are presented in Figure 4.61. The strengths measured at 7 and 28 days show the standard deviation in the range of 4% to 9%. The compressive strength of normal weight aggregate RCCP containing 12% cement at 7 and 28 days was found 31.4 and 43.1 MPa and this value for normal weight aggregate RCCP containing 15% cement is 33.7 MPa and 47.8 MPa, respectively. However, the 7-day compressive strength of RCCPs with 12% cement containing 25,50,75 and 100%

LECA showed 5, 17, 26 and 30% decrease, respectively and the 28-day compressive strengths showed 8, 20, 36 and 44% decrease in comparison with reference RCCP, respectively. Also, this reduction of compressive strength was about 5,13, 19 and 24% at 7-day and 5, 17, 32 and 40% at 28-day for RCCP containing 15% cement, respectively. The results show that the strength loss for RCCPs containing LECA at 28-day is more that 7-day. This is may be due to when cement hydration is almost completed and there is a stronger bond at 28-day, the strength of aggregate has a significant role in strength of concrete. The size, content, shape and texture of aggregate have a significant effect on strength of concrete (Vishalakshi et al., 2018). In addition, as seen in Figure 4.73, the compressive strength increased with increase of time due to hydration process development. However, this increment was not considerable for RCCPs containing 75 and 100% LECA at both cement contents. This could be attributed to ceiling strength of RCCPs containing 75 and 100% LECA that obtained at 7-day. In LWAC, the ceiling strength is the highest strength of concrete that could be obtained irrespective to the development of age (Shafigh et al., 2018). It has reported that LECA concrete reached its ceiling strength at 7 days (Mahmud et al., 2013).

The compressive strength of RCCP typically ranging from 28 to 41 MPa (Harrington et al., 2010). ASTM C 330-89 specified a 28-day cylinder compressive strength of 17 MPa for concrete. According to ACI 325.10R, the minimum 28-day compressive strength of 27.6 MPa is needed for RCCP, as the main structural layer. The results indicate that the compressive strength of all RCCPs containing LECA as coarse aggregate, except RCCP with 12% cement containing 100% LECA, was more than the minimum allowable strength for the main structural layer.

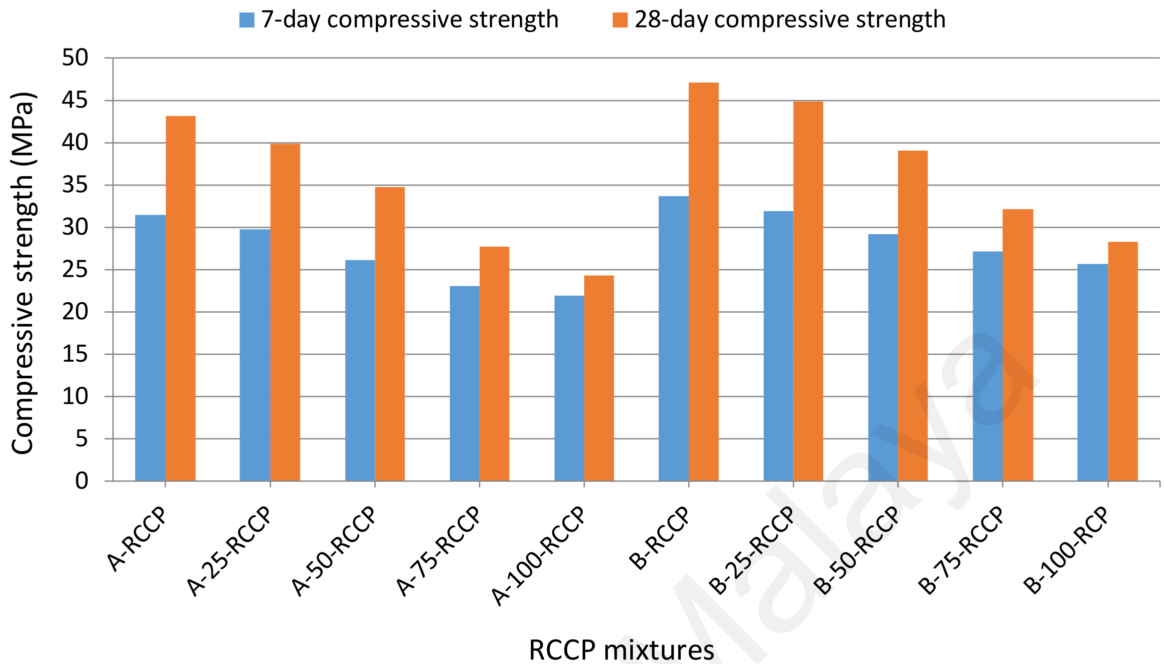


Figure 4.61: Results of compressive strength for RCCPs with 12% and 15% cement

4.7.1.4 Specific strength

The ratio of strength to weight of material is known as specific density. Increasing the strength of material or decreasing its specific gravity would result in a higher specific strength (Li, 2011). The specific strength for normal weight aggregate RCCPs with 12% and 15% cement were 18.1 and 19.5 kN m/kg, respectively. However, this value increase by 18.3 and 20 kN m/kg for RCCPs with 12% and 15% cement containing 25% LECA, respectively. The specific strength of RCCPs with 12% cement content containing 50, 75 and 100% LECA was 17.4, 14.4 and 13.5 kN m/kg, respectively and this value for RCCPs with 15% cement content was 18.9, 16.3 and 15.2 kN m/kg, respectively. The specific strength for LWAC containing LECA is reported about 17.03 kN m/kg (Shafigh et al., 2014).

The results show that although RCCPs with 12% and 15% cement containing 25% LECA as coarse aggregate have lower compressive strength than the normal weight aggregate RCCP but they have higher specific strength than normal weight aggregate RCCP. In addition, the specific strength for RCCPs containing 50% LECA as coarse aggregate for both cement content was comparable with normal weight aggregate RCCP. Therefore, the incorporation of LECA by 50% as coarse aggregate in RCCP is much more preferable somewhere that either the strength or the dead load of structure is important.

4.7.1.5 Splitting tensile strength

The splitting tensile strength results of the various mixtures at 7-day and 28-day are shown in Figure 4.62. The standard deviation for the splitting tensile strength results was 4-10%. The splitting tensile strength shows the same trend with compressive strength, showing the higher values of 3.1 and 4.6 MPa for normal weight aggregate RCCPs with 12% cement and 3.4, 4.9 MPa for normal weight aggregate RCCPs with 15% cement at 7-day and 28-day, respectively.

Also, substituting 25, 50, 75 and 100% LECA in RCCP with 12% cement content decreased the 28-day splitting tensile strength by 20, 34, 47 and 52%, respectively, and the splitting strength for RCCP with 15% cement content decreased by 12, 30, 45 and 51%, respectively.

Generally, the splitting tensile strength of conventional concrete is about 10% of the compressive strength (Mehta & Monteiro, 2006). This ratio ranging from 7 to 13% for normal weight aggregate RCCP (Li, 2004). In this study, the splitting tensile strength of normal weight aggregate RCCPs with 12% and 15% cement contents was about 10.6 and 10.5% of the compressive strength, respectively. The splitting tensile strength of the normal weight aggregate concrete to compressive strength is higher than that of LWAC in the equivalent grade (Haque, 2004). The splitting tensile strength to compressive strength of the high strength LWAC is generally around 6-7% (Omar & Mohamed, 2002). The ratio of splitting tensile strength to compressive strength for RCCPs with 12% cement content containing 25,50,75 and 100% LECA was 9.1, 8.6, 8.5 and 8.9 percent, respectively. Also this ratio for RCCPs with 15% cement and 25, 50, 75 and 100% LECA was 9.5, 8.7, 8.4 and 8.3%, respectively. The ratio of splitting tensile strength to compressive strength depends on the strength level, age, aggregate type, and cement content (Mehta,1986).

The minimum splitting tensile strength of 1.85 MPa for concrete which is used in road construction is determined by British Department of Transport. Thus, all RCCPs containing LECA could be used for road construction.

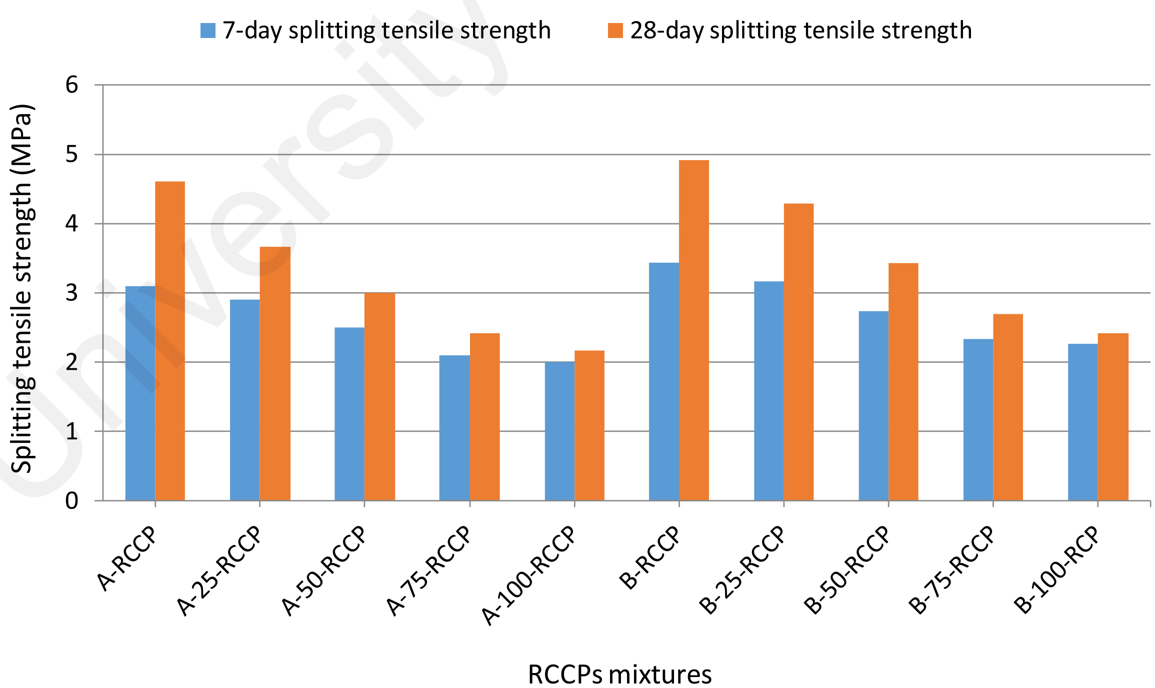


Figure 4.62: Results of splitting tensile strength for RCCPs with 12% and 15% cement

4.7.1.6 Flexural tensile strength

Figure 4.63 shows the flexural tensile strength results. The standard deviation for the flexural tensile strength results was found between 3-9%. Similar decrease in the flexural tensile strength was observed in RCCP with incorporation of the LECA in both cement contents at 7-day and 28-day ages. With the incorporation of 25, 50, 75 and 100% LECA in RCCP with 12% cement, the 28-day flexural tensile strength decreased by 15, 26, 42 and 48%, respectively and those percentages of LECA in RCCP with 15% cement content decreased 28-day flexural tensile strength by 3, 20, 32 and 42%, respectively. Flexural tensile strength is directly related to the unit weight and compressive strength of the concrete mixture (Khayat & Libre, 2014).

Typically, the flexural tensile strength of conventional concrete is about 15% of the compressive strength (Li, 2004). Also, it is reported that the ratio between flexural strength and compressive strength in RCCP is about 0.15, as compared with 0.10 to 0.12 in normal concrete (Harrington et al., 2010). However, a flexural strength of 8–10% of compressive strength is reported by Shetty (2008) for concretes with a compressive strength of more than 25 MPa. In this investigation, the ratio of flexural tensile strength to compressive strength for normal weight aggregate RCCPs with 12% and 15% cement was 12.5 and 12.6% respectively. In addition, this ratio for RCCPs with 12% cement and containing 25,50,75 and 100% LECA was 11.6, 11.5, 11.1 and 11.3%, respectively. Also, the ratio of 12.7, 12, 12.4 and 12% was observed for RCCPs with 15% cement content and 25,50,75 and 100% LECA, respectively. The LEAC has a lower flexural to compressive strength ratio than the normal weight concrete (Domagała, 2011). Omar & Mohamed have reported the ratio of 9–11% for high strength lightweight concrete (Omar & Mohamed, 2002).

The British Airport Authority (BAA) limits the flexural tensile strength to 4 MPa at 28 days. Thus, RCCPs with 12% cement content containing 25 and 50% LECA and also RCCPs with 15% cement containing 25, 50 and 75% LECA as coarse aggregate could be applied as airport pavement. It should be noted that the flexural strength of RCCP is generally from 3.5 to 7 MPa ((Khayat & Libre, 2014).

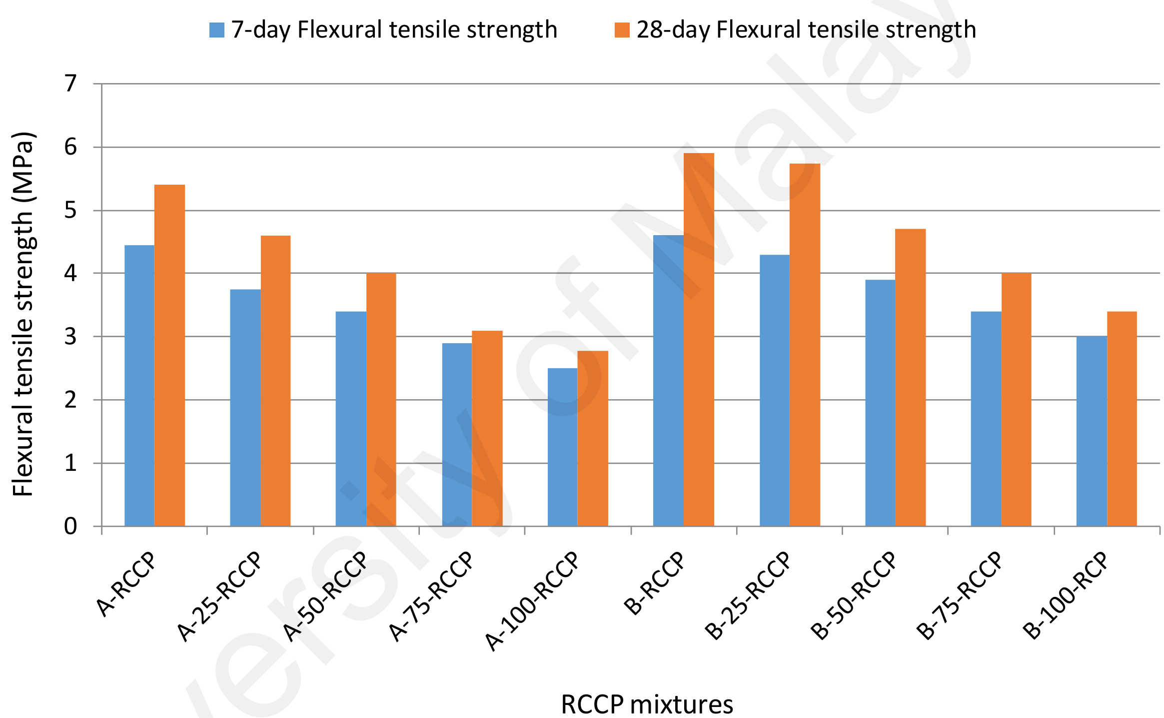


Figure 4.63: Results of flexural tensile strength for RCCPs with 12% and 15% cement

4.7.1.7 Water absorption

Water absorption usually uses as an important factor for quantifying the durability of cementitious systems (Castro et al., 2011). Previous studies indicate that the water absorption values are decreased with increase in the curing time, increase in the degree of consolidation, and decrease in the water-to-cement ratio (Mehta & Monteiro, 2006). Comité euro-international du béton (CEB) (1989) divided concrete into good concrete with water absorption < 3%, average with water absorption 3-5% and poor concrete with water absorption > 5%. The results for initial water absorption after 30 min and final water absorption after 72 h are demonstrated in Figure 4.64. As can be seen the initial surface water absorption of all RCCP mixtures except RCCPs with 12% and 15% cement containing 100% LECA, showed values lower than 3%. In addition, the final water absorption for all RCCPs was more than 3% except A-RCCP, A-25-RCCP, B-RCCP, B-25-RCCP and B-50-RCCP. The results revealed that the water absorption values of RCCP is highly affected by different percentage of LECA as coarse aggregate. Bastos et al (2005) showed that increasing LECA content from 55% to 90% as coarse aggregate in concrete blocks resulted in higher percentage of water absorption. Also, other investigations reported that the incorporation of LECA in the concrete increase the water absorption value (Rashad, 2018).

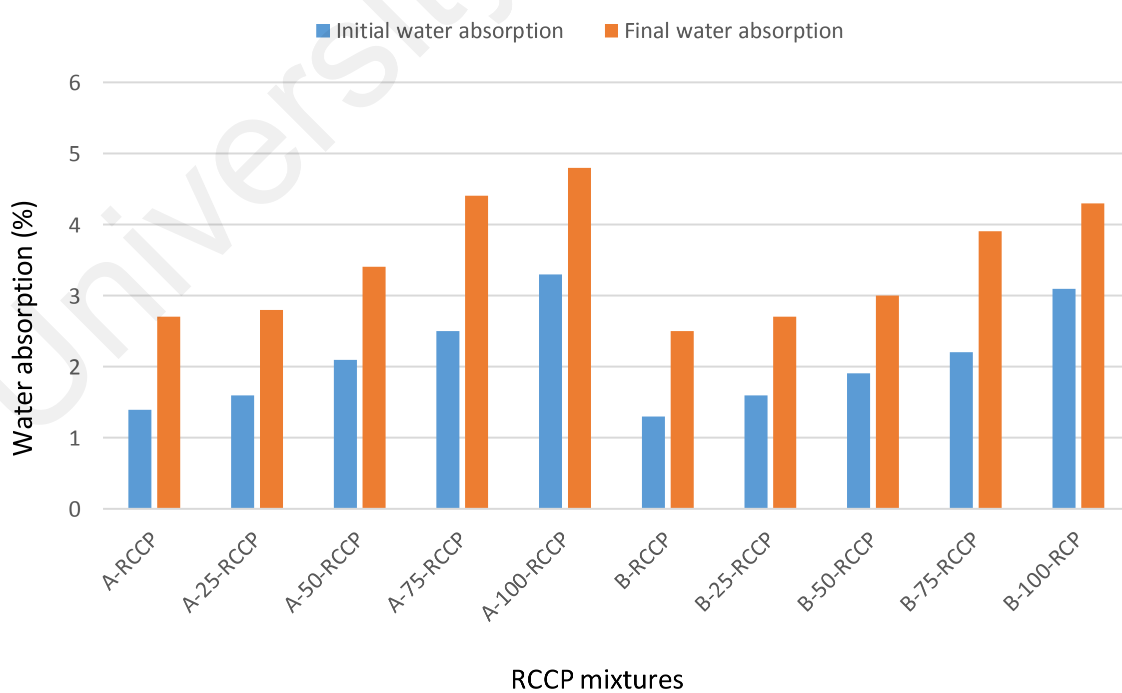


Figure 4.64: Initial and final water absorptions of the RCCPs

4.7.1.8 Porosity

The variation of porosity is similar to the water absorption. Figure 4.65 shows the porosity measurements of RCCPs with different percentage of LECA as coarse aggregate with 12% and 15% cement contents. As seen in the figure, the lowest porosity percentages of 2.9 and 2.7% are for normal weight aggregate RCCPs with 12% and 15% cement content, respectively. However, the porosity values increased by 10, 25, 69 and 82% for RCCPs with 12% cement containing 25, 50, 75 and 100 LECA, respectively. Also those percentages of LECA increased the porosity values by 11, 24, 55 and 70% for RCCPs with 15% cement content, respectively. Kuzu et al (1990) recommended that the porosity of roller compacted concrete is less than 3%. Bogas et al (2015) reported that replacing normal weight coarse aggregate with LECA in concretes showed higher porosity than the reference concrete. Salem et al (2014) found 55.5% increase in the porosity of concrete by substituting normal weight coarse aggregate with LECA (size 4–16 mm).

It should be noted that the cement increment in normal weight aggregate RCCP decreased the porosity by 1%. In this study, increasing cement from 12% to 15% for normal weigh aggregate RCCP decreased the porosity by 9%.

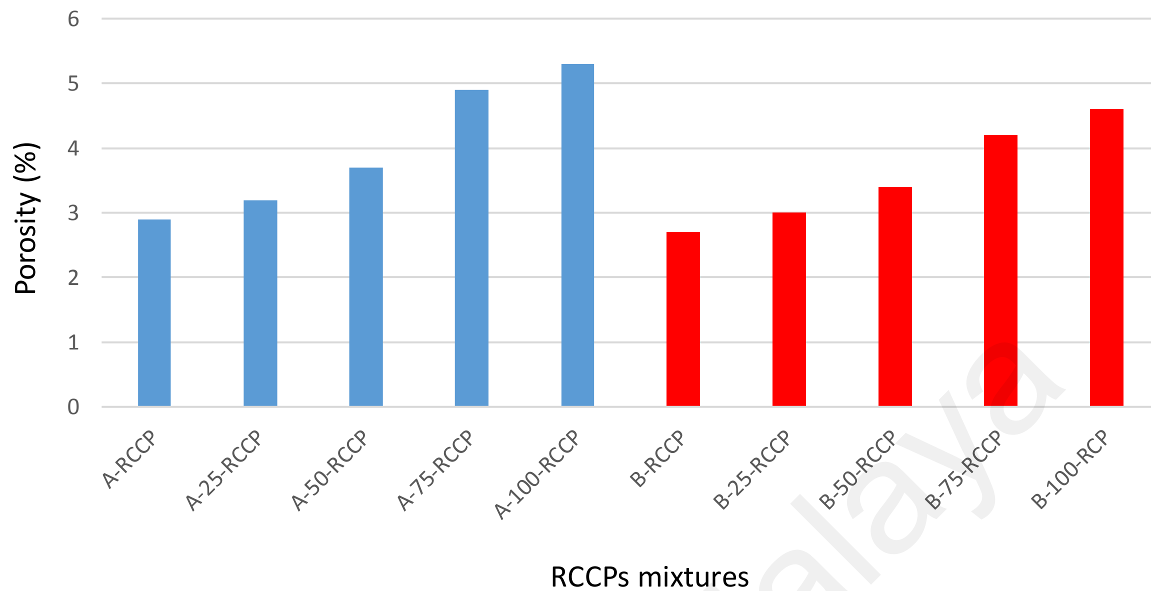


Figure 4.65: Porosity for RCCPs containing 12% and 15% cement at 28-day ages

The relationship between 28-day compressive strength and porosity is presented in Figure 4.66. The figure shows a strong correlation between 28-day compressive strength and porosity. It has been reported that an increment of 1% in the concrete porosity reduces the compressive strength about 3-5 MPa (Kokubu, 1993). In this research by totally replacing LECA as coarse aggregate in RCCP with 12% and 15% cement contents, the porosity increased by 2.4% (from 2.9 to 5.3%) and 1.9% (from 2.7 to 4.6%) and the compressive strength decreased by 44% and 40%, respectively. Therefore, an increment of about 1% in the porosity of light weight aggregate RCCP (100% LECA) with 12% and 15% cement contents leads to approximately 8-MPa and 9-MPa reduction in the 28-day compressive strength, respectively. Therefore, these results indicate that RCCP is more sensitive to its ingredients than conventional concrete.

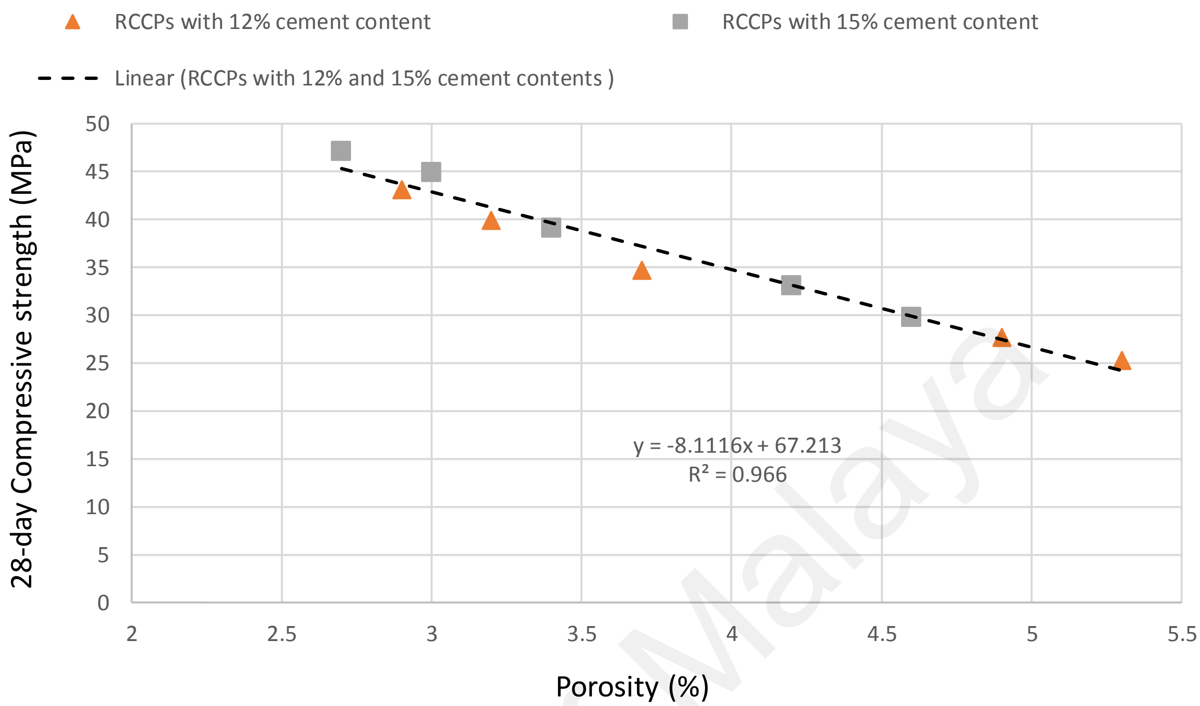


Figure 4.66: Relationship between porosity and 28-day compressive strength

4.7.1.9 Ultrasonic pulse velocity

Ultrasonic Pulse Velocity (UPV) test is very sensitive to homogeneity and density variations and can provide important data for decision making about the conditions of concrete structures (Lorenzi, 2015). Panzera et al (2011) reported that UPV is a non-destructive technique with trusty results on the basis of rapid evaluation for cementitious materials. The range of UPV varies from 3 to 4.5 Km/s (IS 13311, Part I). For excellent quality concrete, good quality concrete and medium quality concrete the UPV must be more than 4.5 Km/s, varying between 3.5-4.5 Km/s and between 3.0-3.5 Km/s, respectively. In this study, the UPV was about 4.7 and 4.9 Km/s (in the range of excellent quality concrete) for normal weight aggregate RCCPs with 12% and 15% cement contents, respectively. This value for all RCCPs except A-75-RCCP, A-100-RCCP and B-100-RCCP was between 3.5-4.5 Km/s (in the range of good quality concrete). In addition, increasing cement from 12% to 15% has a positive effect on the quality and providing dense structure in RCCP production.

Figure 4.67 shows a relationship between compressive strength of RCCP mixtures with different replacement levels of LECA and UPV. The proposed equation could be beneficial for predicting the compressive strength of RCCPs for different conditions in terms of UPV and any percentage of LECA.

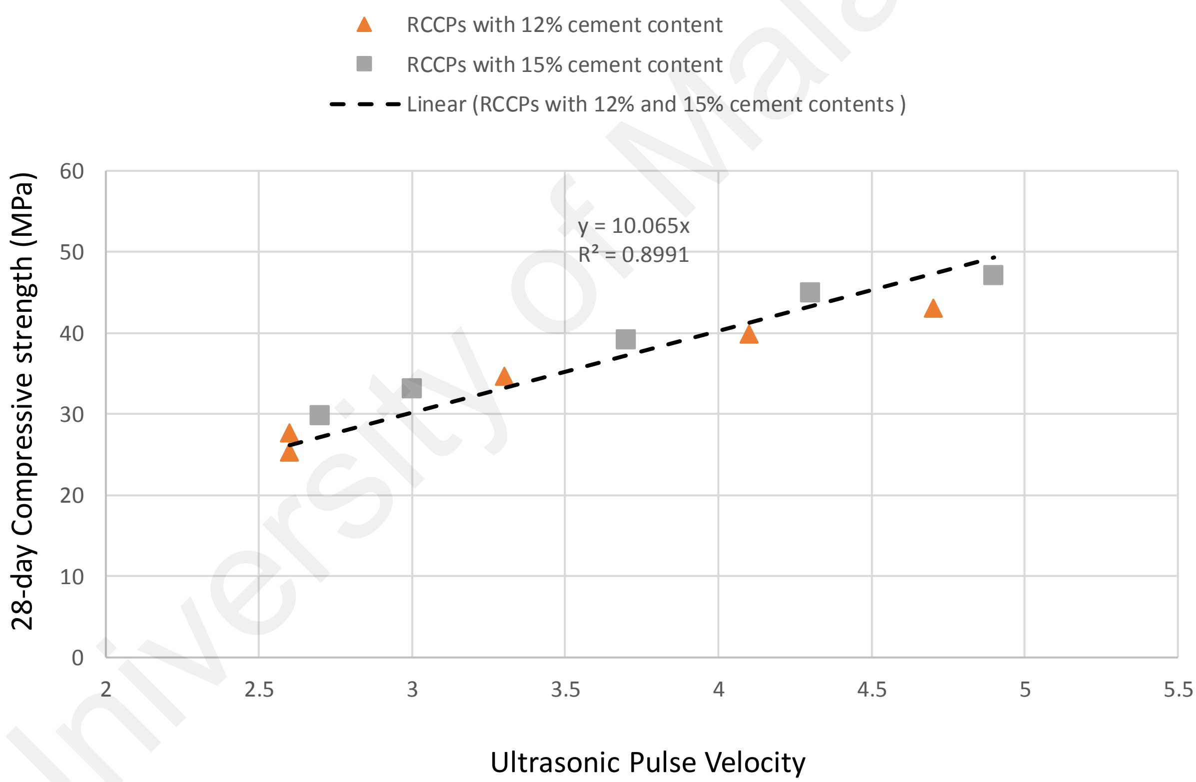


Figure 4.67: Relationship between UPV and 28-day compressive strength

CHAPTER 5. CONCLUSION AND RECOMMENDATIONS

5.1 Conclusions

This research deals with the production of a durable and high-strength RCCP by considering the various ratios of coarse to fine aggregate, cement contents, moisture contents and superplasticizer. In addition, the role of low fines content sand and the effect of LECA in RCCP production as well as establishing the comparative evaluation criteria between RCCP and normal vibrated concrete were investigated. From the research, the following conclusions is drawn according to the research objectives set-out in the beginning of the study.

For first objective, a C/F ratio ranging from 1.2-1.4 is generally optimum. However, for high-quality RCCP in both fresh and hardened states, 12% cement with C/F ratio of 1.2 is recommended for use in the mix. For second objective, low fines content sand did not significantly influence the compressive strength, the porosity and water absorption of RCCPs containing 12% or 15% cement contents. For third objective, the highest mechanical properties and lowest porosity can be reached at moisture content lower than optimum moisture content corresponding to maximum dry density. For fourth objective, the 28-day compressive, splitting tensile and flexural tensile strengths of RCCP was found to be 9%, 4% and 25%, higher than that of NVC specimens, respectively. In addition, the final water absorption and porosity values for RCCP specimens decreased about 8% and 10.6% in comparison with NVCs. For fifth objective, the use of 0.25% and 0.50% superplasticizer increased the 28-day compressive strength about 2% and 9% for RCCPs containing 12% cement and 4% and 14% for RCCPs with 15% cement content, respectively. Also, the use of 0.50% superplasticizer for RCCPs containing 12% and 15% cement decreased the porosity by 8% and 4%, respectively. Finally, for sixth objective, the reduction in the 28-day compressive, splitting tensile and flexural strengths of RCCPs with 12% cement could be in the range of 8-44%, 20-52% and 15-48%, respectively, when LECA was used as coarse aggregate in variation of 25% to 100%. Also, this decrease for RCCPs with 15% cement content was in the range of 5-40%, 12-51% and 3-42%, respectively. Moreover, the substitution of LECA as coarse aggregate in variation of 25 to 100% in RCCPs with 12% cement increased the final water absorption and porosity from 2.8% to 4.8% and 3.2% to 5.3%, respectively. Also, the increment of the final water absorption and porosity was between 2.7% and 4.3% and 3% to 4.6% for RCCPs with 15% cement content, respectively.

5.2 Recommendations

Due to limitations on the methodology and scope of research, there are few concerns and questions arose along with the experimental works in this thesis. The following recommendations are suggested for potential future work:

1. Concrete is the most widely used synthetic material in the world but it is also a significant source of greenhouse gas emissions. Therefore, introducing a substitution for cement is on the hunt for the most effective and efficient way to develop cost-effective green concrete. RCCP. The use of waste materials in RCCP proportions will produce environmentally-friendly concrete. Therefore, the possibility of using waste materials as cement replacement in RCCP should be investigated.
2. The results showed that the RCCP has dense structure and higher density in comparison with conventional concrete. The use of RCCP in bridge pavement construction, i.e. in where the dead load is important will be a challenge due to its higher density properties. A study on lightweight RCCP could be useful to decrease the dead load of pavement and make RCCP applicable for places where the dead load is important.
3. A delayed concreting result in cold joints is a serious concern in RCCP construction. This is because of RCCP mixture is very dry, therefore, it has high potential capacity to occur cold joint at any horizontal lift surface. These surfaces can result in reduced bond strength with the successive lift, even under moist cure conditions. Therefore, finding maximum time possible to get maximum bonding strength looks to be important parameter in RCCP construction.

5.3 List of Publications and Papers Presented

1. **Mohammad Hashemi,** Payam Shafigh, Mohamed Rehan Bin Karim and Cengiz Duran Atis "The effect of coarse to fine aggregate ratio on the fresh and hardened properties of roller compacted concrete pavement" Journal of Construction and Building Materials (Vol. 169- April 2018, pp. 553-566) (IF=3.485).
2. Payam Shafigh**, Mohammad Hashemi**, Boo Hyun Nam and Suhana Koting "Optimum moisture content in roller-compacted concrete pavement" International Journal of Pavement Engineering **(**Jan 2019, pp. 1-11) (IF=2.322)
3. **Mohammad Hashemi**, Payam Shafigh, Mehdi Abbasi and Iman Asadi "The effect of using low fines content sand on the fresh and hardened properties of roller-compacted concrete pavement". Journal of Case Studies in Construction Materials (Volume 11, 2019 Mar 23: e00230) (Cite Score Tracker 2018:2.72)
4. Payam Shafugh, **Mohammad Hashemi,** Boo Hyun Nam and Iman Asadi "*A comparison between roller-compacted concrete pavement and normal vibrated concrete*" (Got acceptance in journal of Croatian association of civil engineers) (IF=0.51)
5. **Hashemi, M**., Shafigh, P. (2017, November). Sustainable roller compacted concrete pavement using fly ash. Paper presented at 11th ASEAN Postgraduate Seminar, Kuala Lumpur, Malaysia
6. Shafigh, P., **Hashemi, M**. (2017, October). Sustainable roller-compacted concrete pavement–A need for developing countries. Paper presented at Scholar Summit 2017; Focusing on "Shaping the Better World", Jakarta, Indonesia.

7. Abbasi, M., Shafigh, P., **Hashemi, M.**, Rizal, M. (2018, November). The use of rubber tire in roller-compacted concrete pavement – A review. Paper presented at ASEAN Post Graduate Conference, Kuala Lumpur, Malaysia.

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