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MECHANICAL PERFORMANCE OF ROLLER COMPACTED RUBBERCRETE WITH DIFFERENT MINERAL FILLER

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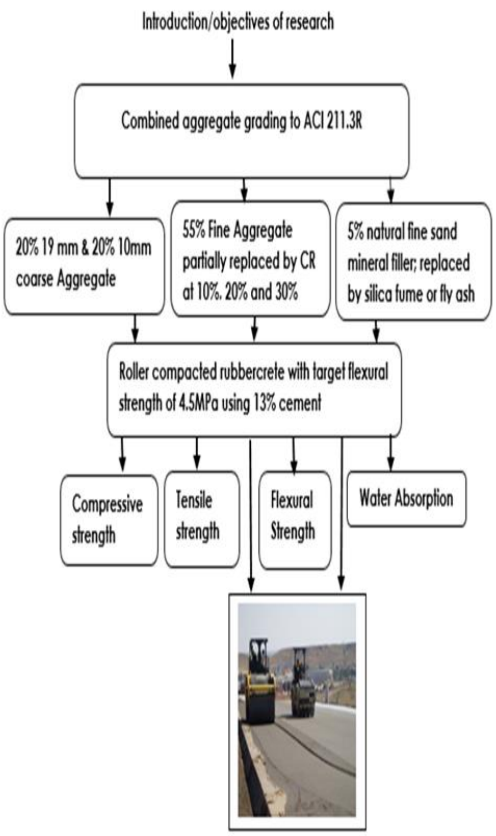
Graphical abstract



Abstract

The rate of waste tire generation globally continues to escalate due to increase in vehicle usage. Scrap tires continue to pose serious environmental, health and aesthetic problems. Due limitation in the recycling of scrap tires, one of the most viable solution is to used crumb rubber from scrap tire as partial replacement to fine aggregate in concrete industry. This is rationalized as the production of concrete hit more than 3.8 billion cubic meters annually, therefore, it could provide a solution on conservation of natural aggregate and as well as improve properties of concrete. However, the major setback in the use of crumb rubber in concrete is loss in strength. In this paper, crumb rubber was used to partially replaced fine aggregate at 0%, 10%, 20% and 30% by volume in roller compacted concrete for pavement applications to produce roller compacted rubbercrete (RCR) to improve its flexural strength and ductility. Several trials were done to achieve the combined grading as recommended by ACI 211.3R, and finally a combination of 55% fine aggregate, 40% coarse aggregate and 5% fine sand as mineral filler was used. In order to mitigate the effect of strength loss, silica fume and fly ash were used to replace natural fine sand as mineral fillers. The Results showed that fresh density, compressive, splitting and flexural strengths decreases with increase in partial replacement of fine aggregate with crumb rubber. However using silica fume as a mineral filler was successful in mitigating loss in compressive, tensile and flexural strengths for up to 20% crumb rubber replacement level, while fly ash as a mineral filler mitigated loss in strength for up to 10% crumb rubber compared natural fine sand mineral filler. The flexural strength was found to increase with 10% crumb rubber for all type of mineral filler

Keywords: Roller compacted rubbercrete, mineral filler, natural fine sand, silica fume, fly ash

Abstrak

Secara global, keadr penjanaan sisi tayar terus meningkat disebabkan oleh peningkatan dalam penggunaan kenderaan. Tayar terpakai menimbulkan masalah yang serius dalam alam sekitar, kesihatan dan estetik. Disebabkan oleh aktiviti kitar semula tayar terpakai yang terhad, salah satu penyelesaian yang palingberdaya maju adalah dengan menggunakan kepingan getah dari tayar terbuang sebagai sebahagian gantain kepada agregat halus dalam industry konkrit. Hal ini rasional berikutan pengeluaran konkrit tahunan mencecah lebih dari 3.8 bilion meter padu, oleh itu, ia boleh menyediakan penyelesaian yang menyumbang kepada pemuliharaan agregat semulajadi di samping meningkatkan cir-cir konkrit. Walaubagaimanapun, halangan utama dalam penggunaan kepingan getah dalam konkrit adalah pengurangan dalam kekuatan. Dalam kajian ini, kepingan getah telah digunakan untuk menggantikan sebahagian agregat halus pada 0%, 10%, 20% dan 30% mengikut isi padu dalam roller compacted concrete untuk aplikasi turapan bertujuan menghasilkan Roller Compacted Rubbercrete (RCR) yang meningkatkan kekuatan lenturan dan kemuluran. Beberapa percubaan telah dilakukan untuk mencapai gabungan penggredan seperti yang disyorkan oleh ACI 211.3R, dan akhirnya gabungan 55% agregat halus, 40% agregat kasar dan 5% pasir halus sebagai pengisi mineral telah digunakan. Dalam usaha untuk mengurangkan kesan kehilangan kekuatan, serbuk silika dan abu terbang telah digunakan untuk menggantikan pasir halus asli sebagai pengisi mineral. Hasil kajian menunjukkan bahawa ketumpatan segar, kemampatan, tegangan belah dan kekuatan lenturan berkurangan dengan peningkatan dalam penggantian sebahagian agregat halus dengan kepingan getah. Walaubagaimanapun serbuk silika sebagai pengisi mineral telah berjaya mengurangkan kehilangan dalam kemampatan, ketegangan dan kekuatan lenturan untuk penggantian sehingga 20% serpihan getah. Manakala abu terbang sebagai pengisi mineral mengurangkan kehilangan kekuatan mampatan sehingga penggantian sebanyak 10% serpihan getah berbanding pengisi mineral pasir halus semulajadi. Kekuatan lenturan didapati akan bertambah dengan 10% serpihan getah untuk semua jenis mineral pasir.

Kata kunci: Roller compacted rubbercrete, pengisi mineral, pasir halus asli, serbuk silika, abu terbang

1.0 INTRODUCTION

As the world population keeps increasing, likewise the number of vehicle usage due to the rapid demand in transportation which is a basic necessity of life. This leads to increase in waste tire generation [1]. Disposal of waste tires is becoming a serious issue to most countries as the world is now focusing towards sustainability of environment. In most highly technological advanced countries it was estimated that every one person generate one waste tire annually and the total number generated annually stands to about 1 billion, with future estimation to reach 1.2 billion by 2030. Globally approximately 4 billion numbers of waste tires are discarded as landfills yearly where more than half of it is dumped without any pretreating [2-5]. These waste tires constitute parts of solid waste where its management is becoming a major concern globally as it is non-biodegradable, it will only be stockpiled when disposed as landfills causing aesthetic and health hazards to the environment by providing shelter and breeding grounds for rodents, mosquitoes, snake etc. [6, 7]. Several attempts of waste tire management are been practiced worldwide, some methods of recycling or reusing waste tires include; production of fuel for cement kiln, in asphaltic pavement, production of carbon black, in marine as artificial reef, in pyrolysis i.e. production of tire derived fuel [4, 8, 9]. Waste tires are also grinded to smaller particles with the steel removed and used as cover for playing ground, surfacing of sport fields, flower bed mulch etc. [8, 10]. However production of carbon black and tire derived fuels are not economically advantage compared to when petroleum products are used and pyrolysis involves emission of large amount of carbon dioxide to the environment, while only a little amount of waste tires are used in the production of asphaltic pavement [4]. The construction industry keeps expanding due to rapid development in technology with concrete been the most used construction material and the most used substance in the world after air and water, one of the major challenges facing the world of construction is the sustainability of the natural materials mostly aggregate as their production involves pollution to the environment [2, 4, 11]. One of the possible ways to reduce the effect of shortage in construction materials, sustainability of environment and waste tire disposal issues is by utilizing the waste tire as partial replacement to natural aggregate in concrete. This will also reduce the cost of concrete by reducing the amount of costly aggregate used [4, 8, 12, 13]. Waste tires are grounded into smaller particles ranging from 75µm to 4.75mm with the steel, fiber, dust and any contaminant removed, and used as crumb rubber to partially replaced fine aggregate in concrete [8]. However, when crumb rubber is used in concrete there is always a reduction in strengths [13-21]. Several methods have been devised to reduce the effect of partial replacement of fine aggregate with crumb rubber in terms of strength loss. Some of these methods include; pre-treatment of crumb rubber with NaOH solution to improve surface roughness and consequently bonding, adding cement replacement materials such as silica fume and fly ash to densify microstructure [13, 14, 22-25]. The most recent is where nano silica was added to concrete containing crumb rubber due to its high pozzolanic reaction, physical properties, pore filling ability, and this method tends to be the most economical and effective way for strength loss mitigation in crumb rubber concrete [26].

According to ACI 207 " A Roller compacted concrete (RCC) is a concrete of zero slump consistency in its fresh state that can be transported, placed and compacted using earth and rock-fill equipment similar to those used in pavement construction. The major advantage of RCC over conventional concrete is construction speed and construction cost. RCC is mostly used for two areas of applications; pavement and dams [27]. A roller compacted concrete pavement (RCCP) is an RCC consisting of coarse aggregate of 19 mm maximum size, higher fine aggregate content, low cementitious materials, low water content and mineral fillers [28]. Mineral fillers are materials of size lower than 75 μm (No 200) sieve, and are required in higher amount in RCC due to lower cement content, so as to increase the paste content and fill the voids, control segregation, and enhance consistency. The most commonly used materials for mineral fillers are fine sand, non-plastic silt, and manufactured. Pozzolanic materials such as fly ash, GGBS and silica fume can be used to replace fine sand, to increase strength performance of RCC [29].

Recently, crumb rubber has been used in roller compacted concrete. Shredded rubber was used to partially replaced coarse aggregate at 5%, 10%, 15%, 20%, 25% and 30% by volume, and it was found that density decreases with increase in rubber content where at 30% replacement the density decreased by 5.8% from 2433 kg/m^3 to 2292 kg/m^3. The compressive strength also decreases with increase in crumb rubber content where a decrease in 28 days strength by 10.3%, 11.5%, 22.4%, 25.2%, 25.3%, and 32% for 5%, 10%, 15%, 20%, 25% and 30% crumb rubber respectively was reported. However, when the shredded rubber were treated with NaOH, compressive strength improved in the range 11% - 28% for 5% -30% crumb rubber [11]. In another study crumb rubber was used to replace fine aggregate from 5% to 35% and cement replaced with 10% silica fume, and it was found that the wet density decreases with increase crumb rubber content where for 35% crumb rubber without silica fume density decreases by 12% while for 35% crumb rubber and 10% silica fume density decreases by 13%, and the reduction in density was attributed to the lower density and specific gravity of crumb rubber compared to fine aggregate it replaced, while the higher reduction in silica fume crumb rubber concrete is due to the lower density and specific gravity of silica fume in relation to cement it replaced. Similarly compressive strength decreased with increasing crumb rubber content where a decrease by 7% and 9% were reported for 5% and 10% crumb rubber without silica fume respectively, when 10% silica fume was added compressive strength increased by 4%, 17%, 13% and 2% for 5%, 10%, 15% and 20% crumb rubber with 10% silica fume respectively compared to those without silica fume [30].

In this paper the effect of partial replacement of fine aggregate with crumb rubber on roller compacted rubbercrete (RCR) for pavement applications was studied and the effect of replacing natural fine sand with fly ash and silica fume as mineral filler was also studied. Crumb rubber (CR) was used from 0% to 30% in multiples of 10%, where fly ash and silica fume were used as mineral fillers at 5%.

1.1 Significance of Research

This research work utilizes crumb rubber in RCC so as to reduce the problems associated with waste tire disposal and sustainability of natural resources mainly aggregates. Silica fume and fly ash are then used as replacement to natural fine sand as mineral filler in roller compacted rubbercrete so as to mitigate the effect of loss in mechanical properties and durability when crumb rubber partially replaces fine aggregate.

2.0 METHODOLOGY

2.1 Materials

The following materials were utilized in this research work:

- Cement: Type 1 Portland cement of grade 43 obtained from Tasek Berhad Malaysia conforming to ASTM C150M-15 was use. Its physical and chemical properties are shown in Table 1.
- Fine Aggregate: Natural river sand with specific gravity (SSD) of 2.65, fineness modulus 2.86, and water absorption 1.24%. its particle size distribution is shown in Figure 1a
- Mineral filler: Natural fine sand with particle size less than 75 μm and specific gravity of 2.61 and fineness modulus of 2.3 was used as mineral filler. Its particle size is determined according to ASTM C117and shown in Figure 1a
- Coarse Aggregate: Two sizes of crushed gravels were used, 19 mm maximum size having a specific gravity of 2.66 and water absorption of 0.48%, 10 mm maximum size aggregate with specific gravity of 2.55 and water absorption 1.05%. The particle size distribution of fine and coarse aggregates as shown in Figure 1b are determined according to ASTM C136.
- Crumb Rubber: Three different sizes of CR were used so that its particle size analysis can be similar to fine aggregate it replaced and

the particle analysis is determined according to ASTM D5644-01. The percentage combinations and sizes of the three CR are; 40% mesh 30 with specific gravity of 0.95, 40% 1-3 mm with specific gravity of 0.90, and 20% 3-5 mm with specific gravity of 0.94.

- Fly Ash: Class F fly ash obtained from YTL cement Berhad Malaysia with properties shown in Table 1 was used as replacement to natural sand as mineral filler.
- Silica Fume: silica fume obtained from YTL cement Berhad Malaysia were used as replacement to natural fine sand as mineral fillers. Its properties is shown in Table 1.

2.2 Experimental Methods

The ratios of aggregates were chosen based on trial so that their combined grading falls between the lower limit and the upper limit of the combined aggregate grading suggested by the US Army Corps of Engineers method [29]. The combined aggregate include 55% of fine aggregate, 20% of 10 mm coarse aggregate, 20% of 19 mm coarse aggregate and 5% of fine sand as mineral filler. The combined grading curve is shown in Figure 1c. In order to evaluate the effect of using silica fume and fly ash as mineral filler in roller compacted rubbercrete (RCR) pavement with partial replacement of fine aggregate with crumb rubber, 12 mixes were prepared by varying the percentage of crumb rubber (CR) content at 0%, 10%, 20% and 30% by volume of fine aggregate, and replacing fine sand with silica fume and fly ash as mineral filler. A target flexural strength of 4.5 MPa was selected and the mix design was developed using the geotechnical concept according to ACI 211.3R/CRD-C161-92, the water and cement contents were obtained using the moisture content-dry density relationship according to ASTM D1557. Table 2 shows the constituent materials developed for each mix

The fresh density was determined according to ASTM C1170, compressive strengths was obtained for 3, 7 and 28 days of curing according to BS EN 12390-7:2009, splitting tensile strength was determined at 3, 7 and 28 days using 100 mm diameter x 100 mm height, according to ASTM C496M-11, while flexural strength was determine at 7 and 28 days using 100 mm x 100 mm x 500 mm beams according to ASTM C293M-10, finally water absorption was determine using 100 mm x 100 mm x 100 mm cubes according to ASTM C642-13. The compaction effort was simulated in the laboratory using a Bosch and the compaction was done using a vibrating hammer. The sample is fully compacted when a ring of mortar is formed across the periphery of the base plate. Three samples were made for each mean where the arithmetic mean value was evaluated. The specimens were stored for 24 hours after casting at 25°C and 50-60% Relative Humidity before demoulding.

Table 1 Properties of cement, silica fume and fly ash

Oxides (%)	Cement	Fly ash	Silica fume
SiO_2	20.76	57.06	91.6
Fe_2O_3	3.35	4.15	1.68
CaO	61.4	9.79	0.91
Al_2O_3	5.54	20.96	1.69
MgO	2.48	1.75	-
K_2O	0.78	1.53	1.19
SO_3	3.44	1.49	0.33
LOI	2.2	1.25	2.75
S.G	3.15	2.3	2.26
Blaine Fineness (m^2/kg)	325	290	-

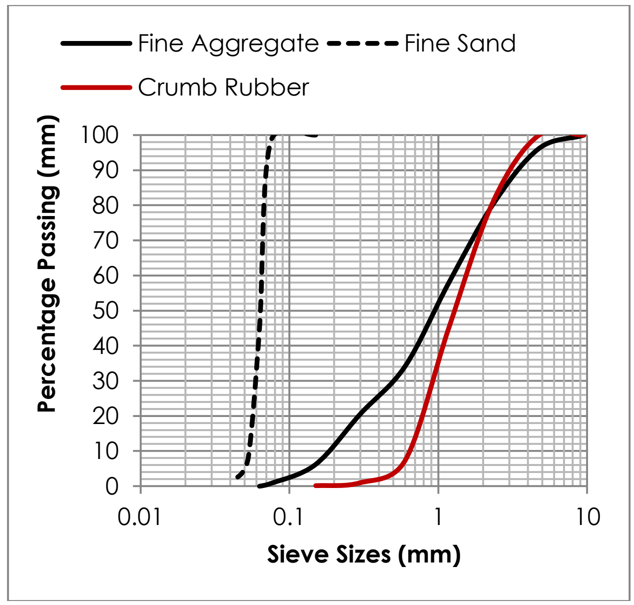


Figure 1a Particle size gradation of fine sand, fine aggregate and crumb rubber

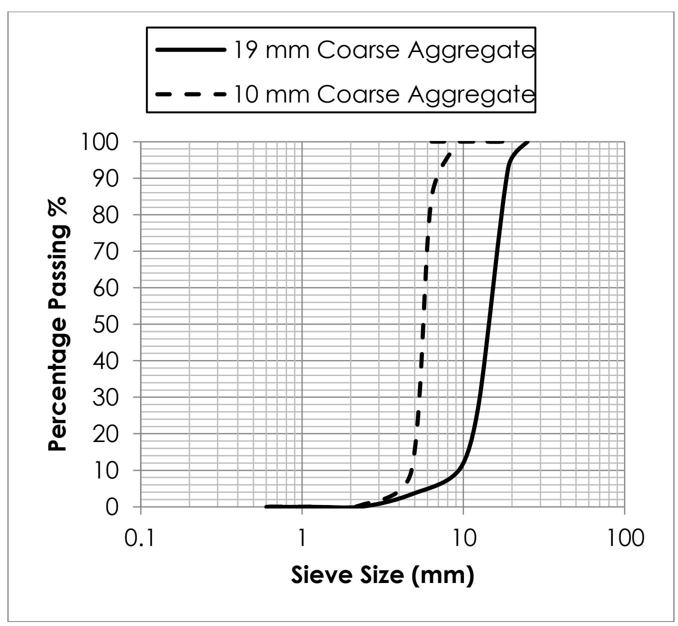


Figure 1b Particle size gradation of coarse aggregate

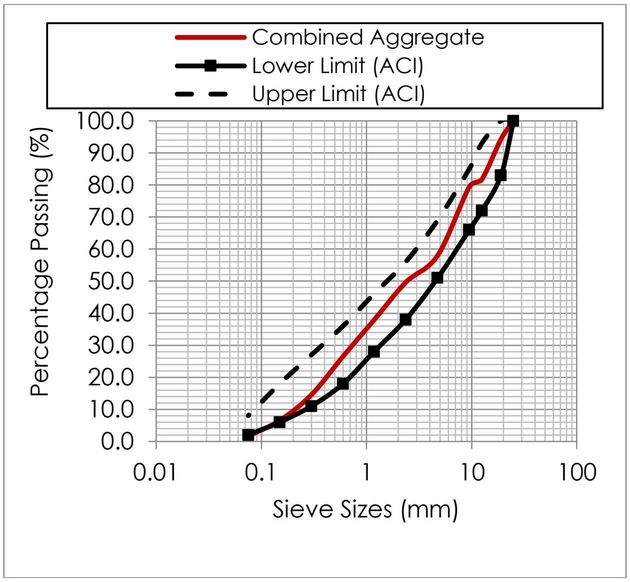


Figure 1c Combine aggregate gradation

3.0 RESULTS AND DISCUSSION

3.1 Fresh Density of RCR

The fresh density of roller compacted rubbercrete (RCR) mix decreases with increase in partial replacement of fine aggregate with CR for all type of mineral filler as shown in Figure 2. As seen when natural sand was used as mineral filler fresh density decreases by 1.4%, 3.75% and 5.7% for 10%, 20% and 30% CR respectively. Similarly, compared to RCR with 0% CR for fly ash mineral filler fresh density decreases by 2.8%, 4.23% and 7.4% for 10%, 20% and 30% CR respectively. While for silica fume as mineral filler a decrease by 1.9%, 3.8% and 5.2% was found for 10%, 20% and 30% CR respectively. This decrease is attributed to the lower density of crumb rubber in comparison to fine aggregate it partially replaced. However, the reduction in fresh density when natural sand was used as mineral filler is lower compared to the findings of findings of other researchers and this is due to the high pressure compaction method adopted when reduces the effect of air entrainment of crumb rubber [30, 31]. From Figure 2 it can be seen that using silica fume is used as a mineral filler yielded the least fresh density, followed by fly ash. This is due to lower specific gravity of silica fume and fly ash compared to natural sand they replaced as mineral filler. Another reason might be due to higher water absorption capacity of natural sand compared to mineral filler and silica fume resulting in more water required to achieve consistency thereby increasing the fresh density.

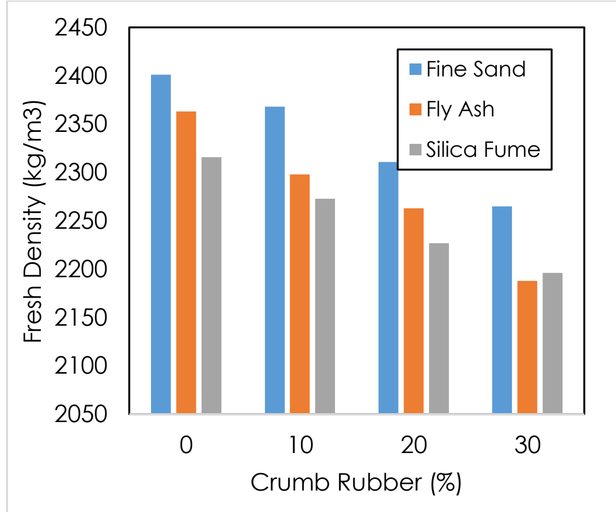


Figure 2 Fresh density of RCR

3.2 Effect of Mineral Filler Type on Water Content of RCR

One of the factors that determine the consistency and strength of RCC is the water content available for mixing and hydration, which is determined using the modified proctor method by measuring the moisture content and the corresponding dry density of a series of RCC mixes. The relationship between the moisture content and dry densities of RCC utilizing different types of mineral fillers is shown in Figure 3. As seen the dry density increased with increasing moisture content until the maximum dry density is achieved, from which the dry density continues to decrease with increasing water content [32]. The corresponding moisture content of the maximum dry density of each mix series is recorded and termed the optimum moisture content (OMC) and is used to obtain the amount of mixing water required to produce a good paste. As seen from Figure 3, the OMC of RCC made with natural fine sand was 5.48% while for RCC with fly ash as mineral filler was 5.95% and for RCC with silica fume mineral filler was 5.82%. The higher water content obtained when fly ash/silica fume replaced natural fine sand as mineral filler in RCC is attributed to the following; higher surface area of fly ash/silica fume compared to fine sand, absorption of water by the fly ash/silica fume for pozzolanic reaction, higher loss of ignition of silica fume/fly ash in comparison to fine aggregate leading to more unburnt carbon which then react which absorbs part of the water

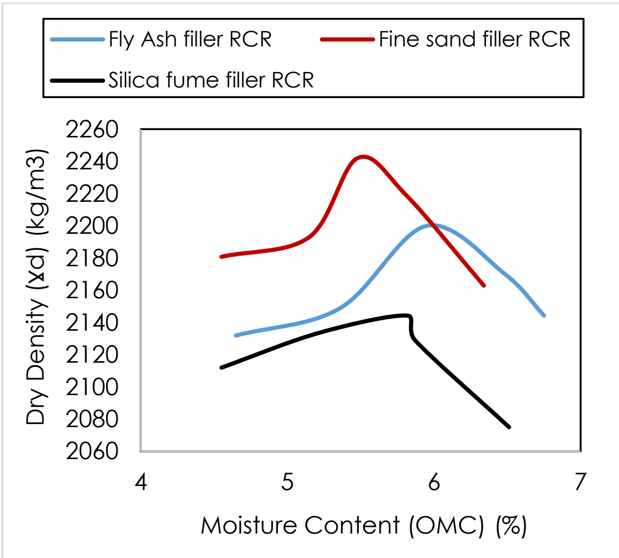


Figure 3 Moisture content-dry density curve of RCC made with different mineral fillers

3.3 Compressive Strength of RCR

The compressive strength of RCR for all type of mineral fillers decreases with increase in partial replacement of fine aggregate with crumb rubber as shown in Figure 4 a, b and c. replacement levels of 10%, 20% and 30% decreases the 28 days compressive strength of natural fine sand mineral filler RCR by 8.8%, 25.2% and 34.6% respectively compared to 0% CR. While a reduction by 10.3%, 26.3% and 33.8% for 10%, 20% and 30% CR respectively compared to its 0% CR for RCR with silica fume mineral filler was found. Similarly for fly ash mineral filler RCR the 28 days compressive strength decreases by 12.3%, 26.5% and 37% for 10%, 20% and 30% CR respectively compared to its 0% CR. The reduction in compressive strength is more pronounced in comparison to tensile and flexural strengths, and is mainly because the compressive strength depends more on the pore volumes and aggregate strength. The reduction in compressive strength with crumb rubber addition is due to the following reasons; poor bonding between crumb rubber particles and cement paste, lower specific gravity, density and stiffness of crumb rubber in relation to fine aggregate it partially replaced [33], it can also be due to crumb rubber entrapping air in its surface during mixing, which increases the thickness of the interfacial transition zone between crumb rubber and cement paste, causing poor bonding with the hardened matrix, and high porosity in the hardened RCR [26]. When silica fume replaces fine sand, the target compressive strength was achieved for all crumb rubber content. Compared to fine sand, replacement with silica fume increases the compressive strength by 32.8%, 46.4%, 46.6% and 50.6% for 0%, 10%, 20% and 30% crumb rubber respectively, while replacement with fly ash increases the compressive strength by 16.8%, 12.3%, 14.8% and 12.5% for 0%, 10%, 20% and 30% crumb rubber respectively. The reason for this increment is due to the ability of the mineral fillers to contribute to strength development through their pozzolanic reactions, more pore filling ability compared to fine sand. The higher strengths for silica fume is due to its higher pozzolanic reactivity compared to fly ash making it to consume more $Ca(OH)_2$ and producing more C-S-H gel which is responsible for strength development, with fly ash having a very low pozzolanic reactivity at early ages of curing. It can also be attributed to the ability of silica fume to densify the interfacial transition zone between cement paste and crumb rubber, and refine the micro structure of the hardened mix compared to fly ash. From the results obtained, replacing fine sand with a pozzolanic material such as silica fume and fly ash mitigate strength loss due to crumb rubber addition to RCC, this can be seen where the compressive strength of RCR with 20% crumb rubber and silica fume mineral filler to be higher than 0% crumb rubber with fine sand mineral filler, while compressive strength of RCR with 10% crumb rubber was higher compared to 0% crumb rubber with fine sand mineral filler.

Table 2 Constituent Materials for RCR mixes

CR (%)	Cement (kg/m³)	Filler Type	Filler (kg/m³)	Fine Aggregate kg/m³	Coarse Aggregate 19mm kg/m³	Coarse Aggregate 10mm kg/m³	Water kg/m³	S.P kg/m³	Mesh 30 kg/m³	1-3 mm CR kg/m³	3-5 mm CR kg/m³
0	268.69	FS	103.76	1148.05	415.03	416.85	98.24	2.69	0	0	0
10	268.69	FS	103.76	1033.25	415.03	416.85	98.24	2.69	48.97	43.95	21.97
20	268.69	FS	103.76	918.44	415.03	416.85	98.24	2.69	97.93	87.89	43.95
30	268.69	FS	103.76	803.64	415.03	416.85	98.24	2.69	146.90	131.84	65.92
0	268.69	SF	103.76	1148.05	415.03	416.85	98.24	2.69	0	0	0
10	268.69	SF	103.76	1033.25	415.03	416.85	98.24	2.69	48.97	43.95	21.97
20	268.69	SF	103.76	918.44	415.03	416.85	98.24	2.69	97.93	87.89	43.95
30	268.69	SF	103.76	803.64	415.03	416.85	98.24	2.69	146.90	131.84	65.92
0	268.69	FA	103.76	1148.05	415.03	416.85	98.24	2.69	0	0	0
10	268.69	FA	103.76	1033.25	415.03	416.85	98.24	2.69	48.97	43.95	21.97
20	268.69	FA	103.76	918.44	415.03	416.85	98.24	2.69	97.93	87.89	43.95
30	268.69	FA	103.76	803.64	415.03	416.85	98.24	2.69	146.90	131.84	65.92

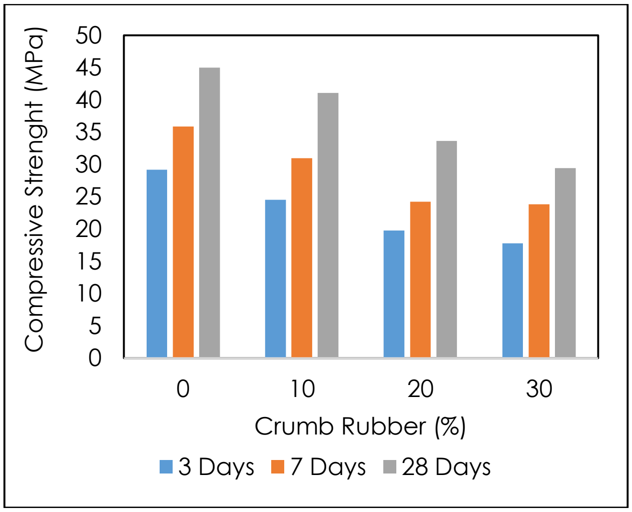


Figure 4a Compressive strength of RCR for natural fine sand mineral filler

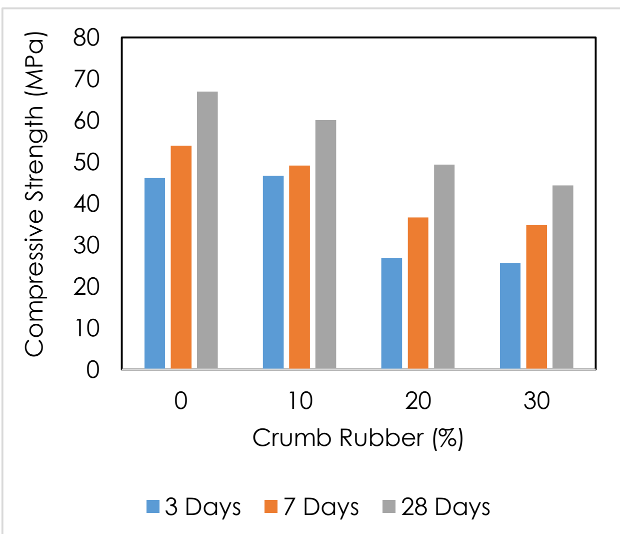


Figure 4b Compressive strength of RCR for silica fume mineral filler

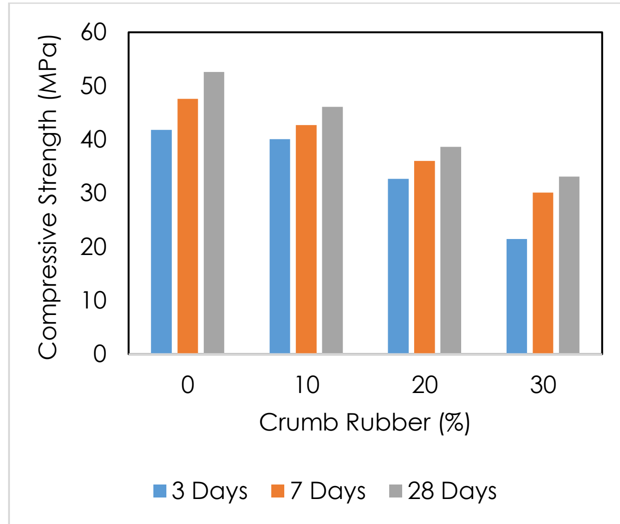


Figure 4c Compressive strength of RCR for silica fume mineral filler

From previous literatures, there is no any developed relationship for mineral filler types used in roller compacted concrete. Hence, in this research relationship between natural sand as mineral filler and silica fume/fly ash as mineral fillers in RCR were developed for different replacement ratios of fine aggregate with crumb rubber from 0% to 30%. The relationship between compressive strength of fine sand mineral filler and silica fume/fly ash mineral filler is shown in Figure 5. As shown there is a good correlation between the compressive strength of fine sand mineral filler and that of both silica fume and fly ash mineral filler. A quadratic relation is proposed for both fine sand-silica fume and fine sand-fly ash mineral fillers compressive strength relations as shown in equations 1a, and b with R^2 values of 0.96 and 0.9582 respectively.

$$C_{SF} = 8.006C_S^{0.5398} \qquad R^2 = 0.9039 \qquad (1a)$$

$$C_F = 5.5778C_S^{0.5681} \qquad R^2 = 0.8541 \qquad (1b)$$

Where the following are 28 days compressive strength of RCR for
C_{SF} = silica fume mineral filler
C_F = fly ash mineral filler
C_S = fine sand mineral filler

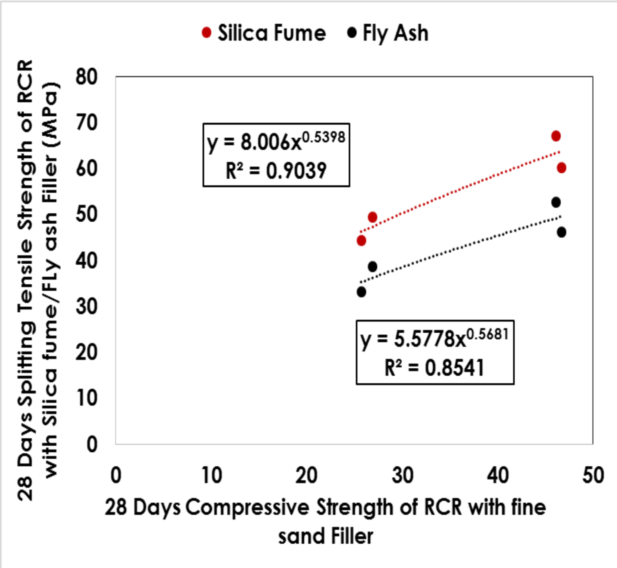


Figure 5 Relation between 28 days compressive strength of fine sand-silica fume minerals in RCR

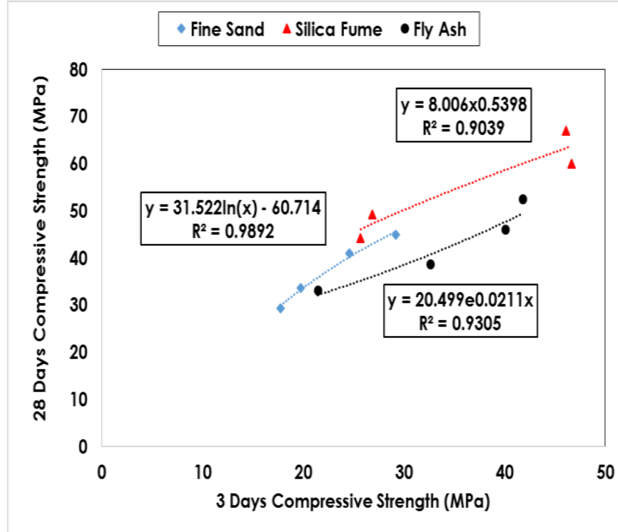


Figure 6 Relation between 28 days and 3 days compressive strengths of RCR for all types of filler

One of the advantage of using roller compacted concrete over conventional concrete is its early strength development [34]. In this paper, the mathematical model for predicting the 28 days compressive strength of RCR with 0%, 10%, 20% and 30% CR as replacement to fine aggregate was developed for fine sand mineral filler and silica fume mineral filler which is shown in Figure 6. As seen there is a good correlation between the variables. A quadratic model was selected for all types of mineral filler as it gives the best correlation. The developed models for RCR made with fine sand filler, fly ash filler and silica fume filler are shown in equations 2a, b, and c respectively.

$$C_{S28} = 31.522 * \ln(C_{S3}) - 60.714 \qquad R^2 = 0.9892 \quad \text{(2a)}$$

$$C_{F28} = 20.499e^{0.0211C_{F3}} \qquad R^2 = 0.9305 \quad \text{(2b)}$$

$$C_{SF28} = 8.006 * C_{F3}^{0.5398} \qquad R^2 = 0.9039 \quad \text{(2c)}$$

Where

C_{S28} and C_{S3} = 28 days and 3 days compressive strength of RCR with natural fine sand mineral filler

C_{F28} and C_{F3} = 28 days and 3 days compressive strength of RCR with fly ash mineral filler

C_{SF28} and C_{SF3} = 28 days and 3 days compressive strength of RCR with silica fume mineral filler

3.4 Indirect Tensile Strength

The indirect tensile strength is measured through the splitting tensile test, with results for all type of mineral filler shown in Figures 7 a, b, and c. As expected the splitting tensile strength decreases with increase in crumb rubber content. For natural fine sand filler, a reduction at 28 days by 8.7%, 18.7% and 27.6% for 10%, 20% and 30% CR respectively compared to 0% CR was found. While for RCR with silica fume as filler its 28 days tensile strength decreases by 2.6%, 15.1% and 25.6% for 10%, 20% and 30% respectively compared to 0% CR .It can be attributed to the poor bonding between crumb rubber and cement paste. However, replacing fine sand with silica fume or fly ash enhances the tensile strength, with silica fume showing higher increment. This is due to the high pore-filling ability and microstructural refinement properties of both silica fume and fly ash. In comparison to fine sand, when silica fume is used as mineral filler, splitting tensile strength increases by 5.7%, 12.7%, 10.4% and 8.7% for 0%, 10%, 20% and 30% crumb rubber respectively. While with fly ash as mineral filler compared to fine sand, splitting tensile strength increases by 1.18%, 7.8%, 3.4% and 6% for 0%, 10%, 20% and 30% crumb rubber respectively. The higher strength gain for silica fume is due to its higher pozzolanic reaction compared to fly ash.

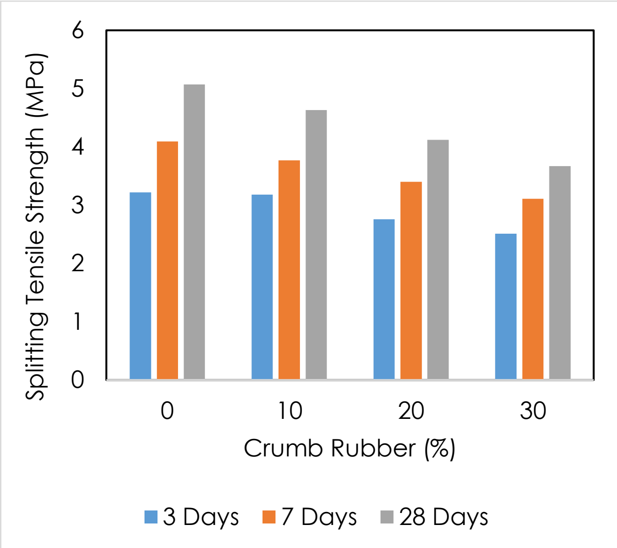


Figure 7a Splitting tensile strength of RCR for Fine sand mineral filler

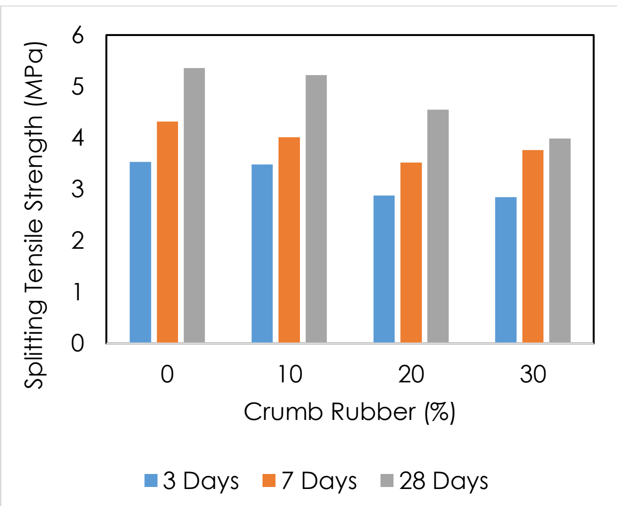


Figure 7b Splitting tensile strength of RCR for silica fume mineral filler

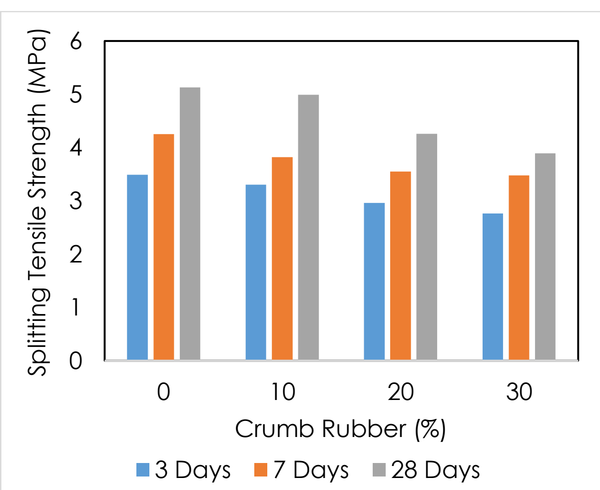


Figure 7c Splitting tensile strength of RCR for fly ash mineral filler

A mathematical model for the relationships between 28 days splitting tensile strength of RCR made with natural fine sand mineral filler and silica fume/fly ash mineral filler was developed as shown in Figure 8 and equations 3. The model was developed for RCR made with partial replacement of fine aggregate with crumb rubber at 0%, 10%, 20% and 30% replacement level. As seen, there is a good correlation between the fine sand and silica fume/fly ash mineral fillers in RCR. A quadratic model was selected because it gave the best correlation. Equations 3a and 3b shown the developed model for fine sand-silica fume and fine sand – fly ash.

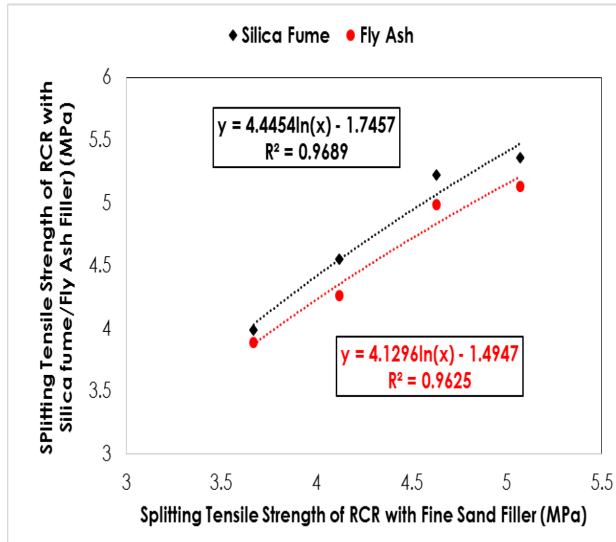


Figure 8 Relation between 28 days compressive strength of fine sand-silica fume/fly ash minerals in RCR

$$T_{SF} = 4.4454 * \ln(T_S) - 1.7457 \quad R^2 = 0.9689 \quad (3a)$$

$$T_F = 4.1296 * \ln(T_S) - 1.4947 \quad R^2 = 0.9625 \quad (3b)$$

Where the following are 28 days compressive strength of RCR for
T_{SF} = Silica fume mineral filler
T_F = Fly ash mineral filler
T_S = Natural fine sand mineral filler

3.5 Flexural Strength of RCR

The results of flexural strength of RCR for all type of mineral filler is shown in Figures9 a, b, and c. An increase in flexural strength for all mineral filler type when 10% crumb rubber partially replaced fine aggregate was found. For natural fine sand mineral filler the 28 days flexural strength increase by 6.64% for 10% crumb rubber, while for 20% and 30% CR it decreases by 4.94% and 22.7% respectively compared to its 0% CR RCR mix. While for silica fume mineral filler RCR, the 28 days flexural strength increases by 11.91% for 10% CR and decreases by 0.8% and 12.5% for 20% and 30% CR compared to its control mix (0% CR/silica fume mineral filler). For fly ash mineral filler RCR, the 28 days flexural strength increases by 9.45% and 0.92% for 10% and 20% CR respectively, and decreases by 20.8% for 30% CR compared to its 0% CR RCR mix. This increase can be attributed to the higher bending and deformation resistance of crumb rubber in comparison to fine aggregate it replaced. Beyond 10% replacement level, flexural strength decreases with increase in partial replacement of fine aggregate with crumb rubber, which is caused due to poor bonding of the crumb rubber with cement matrix. Replacing fine sand with silica fume as mineral filler enhances the 28 days flexural strength by 1.08%, 6.1%, 5.5% and 14.4% for 0%, 10%, 20% and 30% crumb rubber respectively compared to fine sand. While fly ash as mineral filler increases the 28 days flexural strength by 0.93%, 3.04%, 7.14% and 3.4% for 0%, 10%, 20% and 30% crumb rubber respectively compared to fine sand. This increment can be attributed to enhancement of bonding between cement paste and crumb, in combination to pore filling ability of both fly ash and silica fume compared to fine sand.

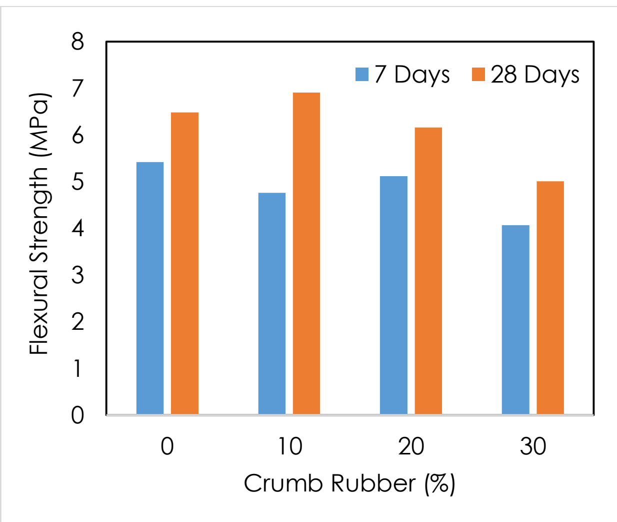


Figure 9a Flexural strength of RCR for natural fine sand mineral filler

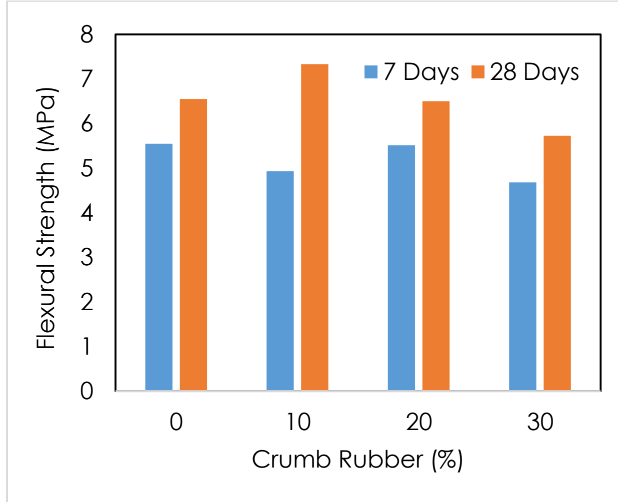


Figure 9b Flexural strength of RCR for silica fume mineral filler

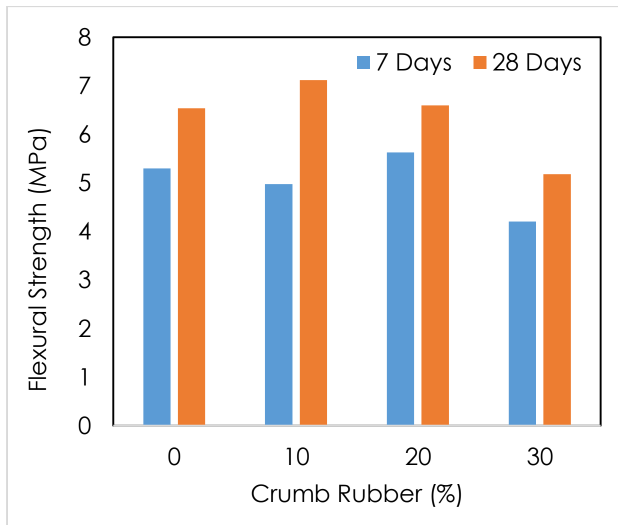


Figure 9c Flexural strength of RCR for fly ash mineral filler

A mathematical model for the relationship between the flexural strength of natural fine sand mineral filler and silica fume/fly ash mineral filler was developed for RCR with partial replacement of fine aggregate by crumb rubber at 0%, 10%, 20% and 30% as shown in Figure 10. As seen, there is a good correlation for all the models developed. A quadratic model for fine sand and silica fume mineral filler was selected as it gives the best line of fit as shown in equation 4a, while for fine sand-fly ash mineral filler a logarithmic model was selected as it gives the best correlation as shown in equation 4b.

$$F_{SF} = 3.1191e^{0.1197F_S} \qquad R^2 = 0.9354 \tag{4a}$$

$$F_F = 5.8624 * \ln(F_S) - 4.238; \; R^2 = 0.9683 \tag{4b}$$

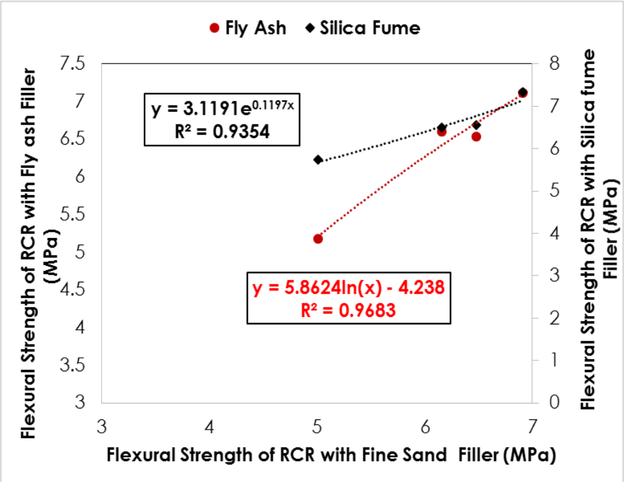


Figure 10 Relation between 28 days flexural strength of fine sand-silica fume/fly ash minerals in RCR

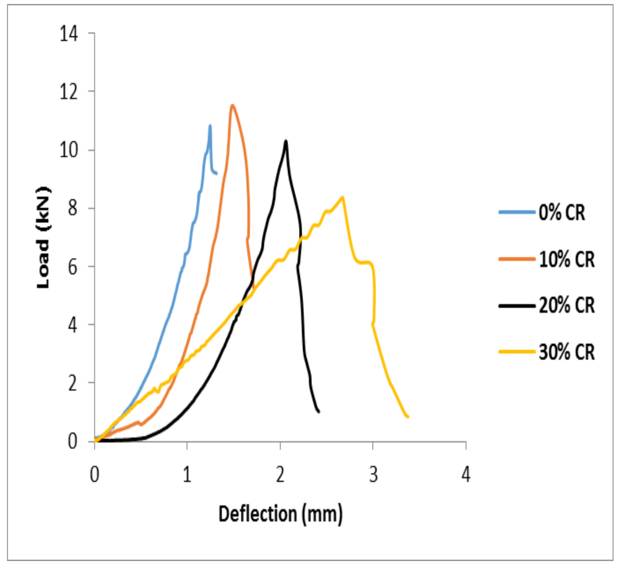


Figure 11 Load-deflection curves for RCR with Fine sand mineral filler

3.5.1 Ductility and Flexural Toughness

One of the advantages of utilizing crumb rubber in concrete is its ability to increase the ductile behavior of concrete due to its high elastic and deformation properties. Figure 11 and 12 shows the load deflection curve and failure modes of RCR made with natural fine sand as mineral filler and containing 0%, 10%, 20% and 30% CR as replacement to fine aggregate. As seen from Figure 11, the slope of 0% CR tends to be the steepest while that of 30% CR is the gentlest slope. This implies that the deflection in 30% CR RCR increases gradually meaning failure will not occur catastrophically. Similarly, when subjected to fatigue loadings, higher CR RCR will resist higher number of cycles before failure compared to RCR with low CR. After attaining the maximum load, higher CR RCR shows more post cracking behavior compared to lower CR RCR as shown in Figure 11 and 12. This makes it to be a good material for use in RCC pavement as it is subjected to repetitive cycles of loadings from moving traffic. The energy absorption capacity can be measured by calculating the toughness which is the area under the load-deflection curve and was found to be 5.07 Knmm, 6.26Knmm, 7.03 Knmm and 13.67 Knmm for 0%, 10%, 20% and 30% CR respectively, this findings is similar to those of previous researchers The main reason for the increase in ductile behavior of RCR is due to the fact that crumb rubber is a better material for absorbing energy and leading to a higher plastic deformation at time of failure [35], and the crack bridging mechanism, twisting, compressing and bending properties of CR compared to fine aggregate [36].

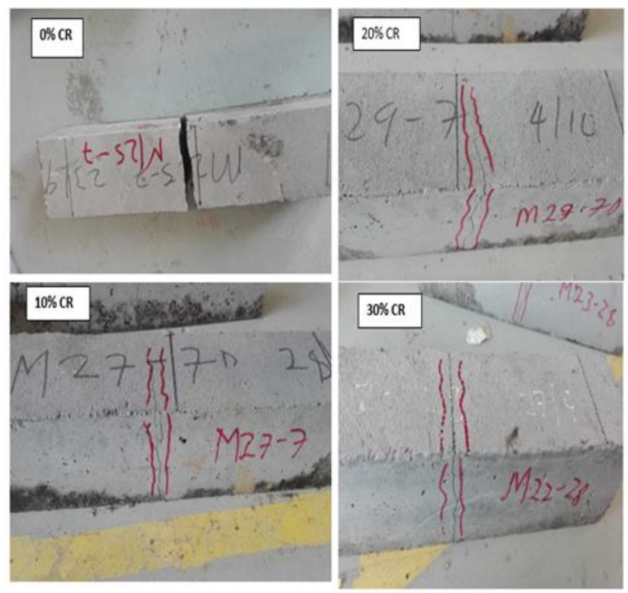


Figure 12 Failure mode of RCR made with fine sand filler

3.6 Water Absorption

The water absorption test is one of the factors to measure how durable the RCR is. The results of the water absorption of RCR for all types of mineral fillers are shown in Figure 13. The results of shows that for all type of mineral filler the water absorption rate increases with increment in partial replacement of fine aggregate with crumb rubber. When natural fine sand is used as mineral filler in RCR, the water absorption increased by 8.3%, 25.2% and 49% for 10%, 20% and 30% CR replacement levels respectively. When silica fume replaced natural sand as filler in RCR the reduction in water absorption became less where it reduced by 2.4%, 10.1% and 33.3% for 10%, 20% and 30% CR replacement level respectively. Similarly using fly ash as mineral filler in RCR also reduces the lost in water absorption compared to fine sand mineral filler. The water absorption increased by 3.7%, 25% and 39.3% for 10%, 20% and 30% CR replacement levels respectively. The reduction with increment in crumb rubber is attributed to more pores created by the crumb rubber in the hardened matrix caused by entrapped air on the surface of crumb rubber during mixing, and it may be due to the weak interfacial zone between crumb rubber particles and cement paste which absorbs water. Compared to control mix (0% crumb rubber for fine sand mineral filler), replacing fine sand with silica fume reduces the water absorption by 18.4%, 16.5% and 10.2% for 0%, 10% and 20% crumb rubber respectively. While using fly ash as mineral filler reduces the water absorption by 7.3% and 3.9% for 0% and 10% crumb rubber respectively. The reduction in water absorption using silica fume and fly ash as mineral filler can be attributed to the both pore filling ability of the pozzolanic material. Another reason is due to pozzolanic reactions of silica fume or fly ash with cement where silicon oxide (SiO_2) from the pozzolanic materials will react with the $Ca(OH)_2$ from cement reaction with water to form more C-S-H gel, which is also responsible for densification of hardened microstructure.

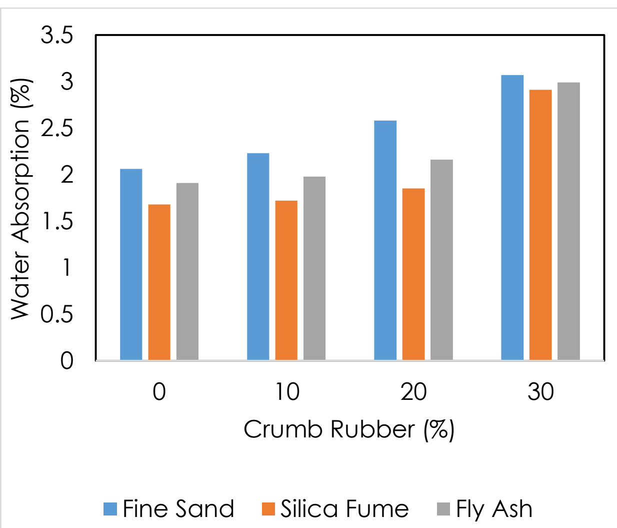


Figure 13 Water Absorption of RCR for all types of filler

A mathematical model is developed for the relationship between water absorption of natural fine sand mineral filler and silica fume/fly ash mineral fillers as used in RCR with percentage replacement of fine aggregate with crumb rubber at 0%, 10%, 20% and 30% as shown in Figure 14. There is a good correlation between the relationship of fine sand mineral filler and silica fume/fly ash mineral filler as used in RCR. A quadratic model is selected for both types of mineral filler as it gives the best correlations as shown in Equations 5a and 5b for fine sand-silica fume and fine sand-fly ash mineral fillers respectively.

$$W_{SF} = 0.5145e^{0.5437W_S} \qquad R^2 = 0.8836 \qquad (5a)$$

$$W_F = 0.7386e^{0.4434W_S} \qquad R^2 = 0.9381 \qquad (5b)$$

Where WSF = Water absorption of RCR with silica fume mineral filler
WF = Water absorption of RCR with fly ash mineral filler
WS = Water absorption of RCR with natural fine sand mineral filler.

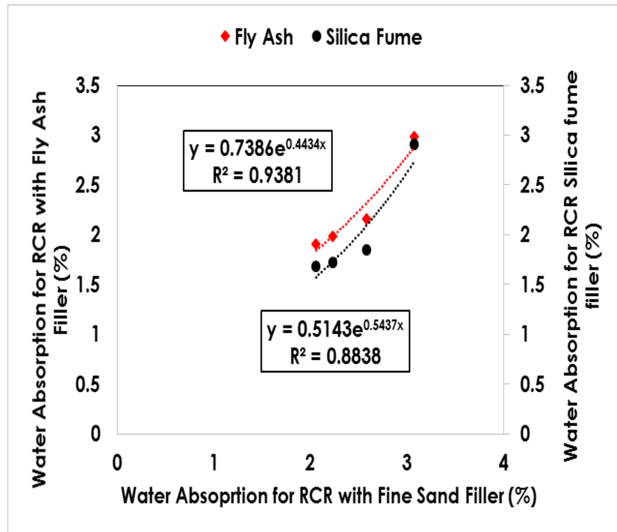


Figure 14 Relation between 28 days flexural strength of fine sand-silica fume/fly ash minerals in RCR

4.0 CONCLUSION

This paper investigated the effect of replacing fine sand as mineral filler with silica fume and fly ash. The results obtained showed that crumb rubber addition decreases the fresh density, compressive strength, splitting tensile strength and flexural strength. The following conclusions can be drawn

1) The fresh density of RCR with silica fume and fly ash as mineral filler were lower than that of RCR with natural fine sand as mineral filler
2) The compressive, splitting tensile and flexural strengths of silica fume as mineral filler were highest, followed by fly ash mineral filler, and least is using natural fine sand as mineral filler.
3) Silica fume as a mineral filler is successful in mitigating strength loss for up to 20% crumb rubber replacement level, while fly ash as a mineral filler mitigated strength loss for 10% CR replacement only
4) Replacing 10% of fine aggregate with crumb rubber increases the flexural strength for all type of mineral filler.
5) The water absorption of RCR increases with crumb rubber addition for all type of mineral

filler, however silica fume and fly ash when used as filler reduces the effect. Silica fume was successful in mitigating of durability loss for up to 20% crumb rubber in RCR while fly ash mitigated for up to 10% crumb rubber.

6) There is a good correlation between the relationship of RCR produced with natural fine sand mineral filler and RCR produced with silica fume/fly ash mineral filler for the following models; compressive strength, tensile strength, flexural strength and water absorption

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