Effect of Polycarboxylate Superplasticizer Dosage on the Mechanical Performance of Roller Compacted Rubbercrete for Pavement Applications

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Abstract: Roller Compacted Concrete (RCC) is a special type of dry mixed concrete having similar ingredients and properties as conventional concrete but with lower water/cement, lower paste content, higher fine aggregate content. RCC should be made in such a way that they will be easier to compact and should have adequate properties for the roller compaction. The best strength in RCC is obtained when the optimum compaction is achieved and this condition can only be attained at the wettest mix that can be able to support vibratory roller without sinking. Water reducing admixtures has been used in RCC to increase its consistency by helping in the distribution of the little paste content, lower its water/cement ratio and improve its strength. In this study, the effect of superplasticizer dosage on the properties of Roller Compacted Rubbercrete (RCR) made by partial replacement of fine aggregate with crumb rubber in Roller Compacted Concrete (RCC) pavement was studied. Superplasticizer was added at 0, 1 and 2% by weight of cementitious materials and fine aggregate was replaced with crumb rubber at 0, 10, 20 and 30%. The results showed that crumb rubber decreases consistency and compressive strength of RCR and increases its flexural strength. Similarly, addition of superplasticizer further decreases consistency of RCR and increases its compressive strength. In addition, the flexural strength of RCR increases with addition of 1% superplasticizer and decreases with addition 2% superplasticizer. The recommended dosage of superplasticizer for use in RCR is 1% by weight of cementitious materials.

Key words: Crumb rubber, superplasticizer, roller compacted rubbercrete, vebe consistency, compressive strength, flexural strength

INTRODUCTION

Roller Compacted Concrete (RCC) is a special type of dry mixed concrete having similar ingredients and properties as conventional concrete but with lower water/cement, lower paste content, higher fine aggregate content, no entrained air (Hesami *et al.*, 2016a; Mehta and Monteiro, 2006). The major advantages of RCC over conventionally placed concrete include high construction speed, reduced construction cost (Mohammed and Loong, 2015). RCC has similar strength and performance properties as conventional concrete but with the economy and simplicity of construction as that of asphaltic pavement with lower maintenance needed and longer service life (Lazaro *et al.*, 2016). RCC is transported and placed using equipment similar to that of asphaltic pavement construction and then compacted using vibratory roller. However, the major benefit of using RCC in pavement over conventional rigid and asphaltic pavement include the rapid construction, reduced maintenance, improved sustainability of resources and lower embodied carbon dioxide (ERMCO, 2013).

Roller compacted concrete pavement mix contains water and cementitious materials and large percentage of aggregate of nominal maximum size not >19 mm which are mixed to form a relatively stiff mix and are placed in layers not >254 mm (10 inch) compacted thickness usually by asphalt paving machine then properly compacted using steel wheel vibratory roller and finally rubber tire rollers used to give a smooth surface to the pavement (Adamu *et al.*, 2016). In order to ensure higher performance and specified engineering properties, RCC should be made in such a way that they will be easier to compact and should have adequate properties for the roller compaction. The major factors that influence the compactability of RCC are the water to cementitious materials content the mineral aggregate gradation and size the shape and the amount of fine and coarse aggregate in the mix (Hesami *et al.*, 2016b). In addition, the

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best strength in RCC is obtained when the optimum compaction is achieved and this condition can only be attained at the wettest mix that can be able to support vibratory roller without sinking (Mehta and Monteiro, 2006). This method does not utilizes the conventional concept of minimizing the water-to-cement ratio to maximize the concrete strength the best compaction gives the best strength and the best compaction occurs at the most wet mix that will support the operating vibrating roller.

Water reducing admixtures has been used in RCC to increase its consistency by helping in the distribution of the little paste content, lower its water/cement ratio and improve its strength. Also, its application in RCC can be much higher than in conventional concrete due to the drier nature of RCC. However, the dosage of the admixture should be obtained from the laboratory prior to application as its excess might result to little improvement and sometimes harmful effect on the performance of RCC (Fuhrman, 2006). However, the effect of water reducing admixtures in RCC is mainly dependent on the amount of materials finer than 75 µm which is used to increase the cohesiveness and reduce the pore volume in the paste (Nanni *et al.*, 2002).

Crumb rubber has been used in roller compacted concrete pavement as a partial replacement to fine or coarse aggregate. Meddah *et al.* (2014) studied the effect of shredded rubber as partial replacement to cement in roller compacted concrete pavement they observe a decrease in fresh density and improved consistency with increasing partial replacement. They reported a 5.8% decrease in fresh density and 30.3% increase in vebe time for 30% replacement level they also reported a decrease in mechanical properties and water absorption with increment in shredded rubber content where for 30% replacement at 28 days, 32, 23.7, 31.8 and 52% decrease in compressive strength, tensile strength, flexural strength and modulus of elasticity, respectively while water absorption declines by >70%. Treating the shredded rubber with NaOH solution and gluing it with sand using resin results in recovering 11-28% of compressive strength and 15-20% of tensile strength. Fakhri (2016) studied the effect of partial replacement of fine aggregate with crumb rubber in RCC pavement and reported decrease in fresh density and water absorption in RCCP with increment in replacement of fine aggregate with crumb rubber they found the reduction to be even higher when silica fume partially replaced cement a 12 and 13% reduction was observed for 35% crumb rubber and 35% crumb rubber plus 10% silica fume, respectively. They also reported an increase in compressive strength at 28 days by 7 and 9% for 5 and 10% crumb rubber

replacement, respectively. The increase in strength became higher when 10% of the cement was replaced with silica fume where 4, 17, 13 and 2% increment for 5, 10, 15 and 20% crumb rubber, respectively containing 10% silica fume. Flexural strength increases at 28 days by 9 for 5% crumb rubber. Aghayari *et al.* (2016) partially replaced fine aggregate with recycled crumb tire and reported decrease in fresh density by 6 for 10% replacement level, while compressive strength decreases by 10.58 and 32.8% for 5 and 10% replacement and tensile strength decreases by 21.8 and 41.4 for 6 and 10% replacement level.

In summary, few literatures studied the effect of using crumb rubber as partial replacement of fine aggregate in RCC pavement and no available study on the use of superplasticizer in RCC pavement as most researchers concluded it is difficult to be used in RCC pavement due to its dry nature. However, based on the literatures reviewed, water reducing admixtures can be used in RCC to increase strength and lower the amount of water used. Therefore, this study aimed at determining the effect and dosage on superplasticizer on the consistency, compressive strength and flexural strength of Roller Compacted Rubbercrete (RCR). RCR were produced by partially replacing fine aggregate with crumb rubber in RCC.

MATERIALS AND METHODS

The details of the materials used in this study include.

Cement: Ordinary portland type 1 cement which conforms to ASTM C150M-15 having specific gravity of 3.15 and chemical properties as in Table 1 was used.

Fine aggregate: Natural sand with nominal maximum size aggregate of 4.75 mm, specific gravity of 2.65, fineness modulus of 2.86, water absorption of 1.24% and particle size gradation as shown in Fig. 1 was used.

Coarse aggregate: Two sizes of coarse aggregate were used. The 19 mm maximum size aggregate having specific gravity of 2.66 and absorption of 0.48% and chips of 6.3 mm maximum size with specific gravity of 2.55 and absorption of 1.05%. Their particle size analysis is shown in Fig. 1.

Crumb rubber: Three sizes of crumb rubber were combined so as to achieve gradation similar to fine aggregate used. After several series of trial combinations, using sieve analysis according to ASTM D5644, final

Table 1: Properties of fly ash and silica fume

Oxides (%)	SiO_2	Fe_2O_3	CaO	Al_2O_3	MgO	K_2O	SO_3	P_2O_5	LOI	SG	Blaine fineness (m^2/kg)
Cement	12.1	4.18	75.9	1.92	1.03	0.486	3.44	-	1.1	3.15	325
Fly ash	34.5	23.6	19.0	12.8	2.27	2.080	1.49	1.27	-	2.30	
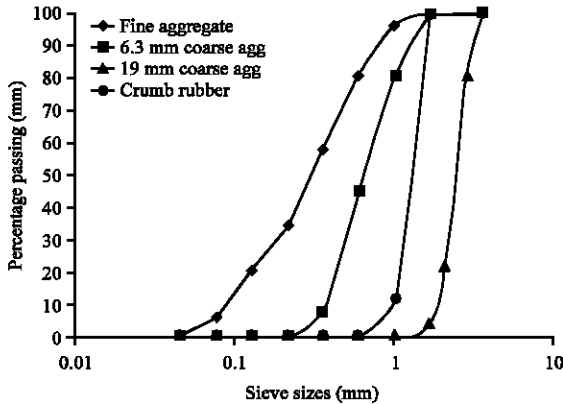
Fig. 1: Sieve analysis of aggregate

Fig. 2: Combined aggregate gradation

proportion of 40% 0.595 mm (mesh 30) size, 40% 1-3 mm size and 20% 3-5 mm size were used. Their combined particle size curve is shown in Fig. 1. In order to obtain the sizes of crumb rubber to be similar to that of fine.

Mineral filler: One of the basic requirement for any RCC pavement is that 2-8% of the aggregate should be materials finer than 75 µm so as to produce a cohesive paste with lower void contents. In this study, fly ash conforming to ASTM C612 and ASTM C311 having properties shown in Table 1 was used as a filler (material finer than 75 µm).

Superplasticizer: Polycarboxylate base viscocrete-2044 which conforms to the requirements of EN 934-2 was used.

Mix proportioning: The mix proporti oning was done using the soil compaction geotechnical approach according to ACI, 211.3R-02 (ACI, 2002). It involves a series of stages.

Firstly, the optimal combinations of fine aggregate, coarse aggregate and mineral filler was determined so that the combine aggregate grading curve falls within the limit recommended by ACI, 211.3R-02 (ACI, 2002) and US army corps of engineers. The combined aggregate gradation curve shown in Fig. 2 was obtained using a combination of 55% fine aggregate, 20% 19 mm coarse aggregate, 20% 6.3 mm chips coarse aggregate and 5% fly ash (mineral filler).

Step 2 is the determination of Optimum Moisture Content (OMC) and Maximum Dry Density (MDD) according to ASTM D, 1557-12e. Here the OMC and MDD
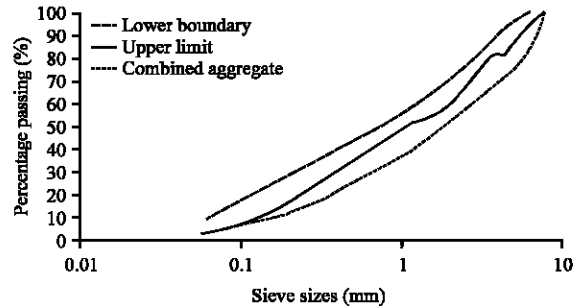
of four RCC mixes produced using different cement contents; 12, 13, 14 and 15% by weigh of dry aggregates were determined. For each cement content five mixes were produced using different water contents from 4.5-6.5% by weight of dry aggregate and the moisture-density curve was plotted. The optimum moisture contents for each RCC mix for different cement contents were then plotted. The optimum moisture content for 12, 13, 14 and 15% cement contents were found to be 5.46, 5.56, 5.92 and 6.09%, respectively as shown in Fig. 3.

Next four RCC mixes were produced using 12, 13, 14 and 15% cement contents using their corresponding OMC obtained from Step 2 as the amount of water for the mix. The 28 days compressive strength and flexural strength of each mix was determined and the relationship between cement content and compressive/flexural strength plotted as shown in Fig. 4.

Based on target flexural strength of 4.8 MPa, 13% cement content was selected which will be used to derive the proportion for all the mixes in the study. Based on the required flexural strength and calculations of constituent materials, a water/cement ratio of 0.42 was found.

Experimental programs: In order to study the effect of superplasticizer dosage on the properties of roller compacted rubbercrete, twelve mixes were produced using 0, 1 and 2% superplasticizer by weight of cementitious materials and replacement of fine aggregate with 0, 10, 20 and 30% by weight with crumb rubber. For 1 and 2 superplasticizer additions the water content was reduced by 12 and 15%, respectively (Malaysia, 2010). The mixes were compared with the control mix produced with 0% superplasticizer and 0% crumb rubber. Table 2 shows the detailed constituent material for each mix. Mix C0S0 is the control mix with 0% superplasticizer and 0% crumb rubber, C30S2 is mix with 30% crumb rubber and 2% superplasticizer.

Table 2: Mixtures constituent materials

| Mix	Cement (kg/m³)	Filler (kg/m³)	Fine aggregate (kg/m³)	Coarse aggregate (kg/m³)	Crumb rubber (kg/m³)	Water (kg/m³)	SP (kg/m³)	W/C ratio
C0S0	268.69	103.76	1148.05	831.88	0.00	111.64	0.00	0.42
C10S0	268.69	103.76	1033.25	831.88	114.89	111.64	0.00	0.42
C20S0	268.69	103.76	918.44	831.88	229.78	111.64	0.00	0.42
C30S0	268.69	103.76	803.64	831.88	344.67	111.64	0.00	0.42
C0S1	268.69	103.76	1148.05	831.88	0.00	98.24	2.69	0.37
C10S1	268.69	103.76	1033.25	831.88	114.89	98.24	2.69	0.37
C20S1	268.69	103.76	918.44	831.88	229.78	98.24	2.69	0.37
C30S1	268.69	103.76	803.64	831.88	344.67	98.24	2.69	0.37
C0S2	268.69	103.76	1148.05	831.88	0.00	94.89	5.37	0.35
C10S2	268.69	103.76	1033.25	831.88	114.89	94.89	5.37	0.35
C20S2	268.69	103.76	918.44	831.88	229.78	94.89	5.37	0.35
C30S2	268.69	103.76	803.64	831.88	344.67	94.89	5.37	0.35
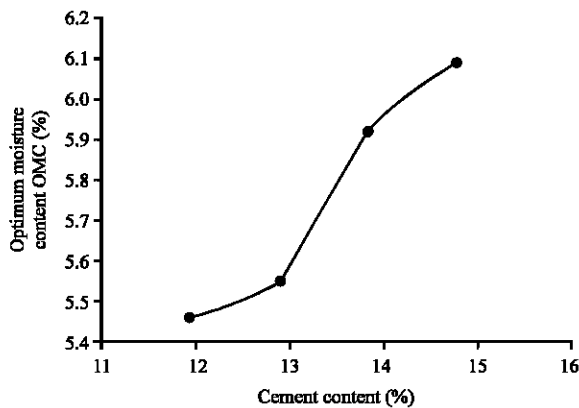
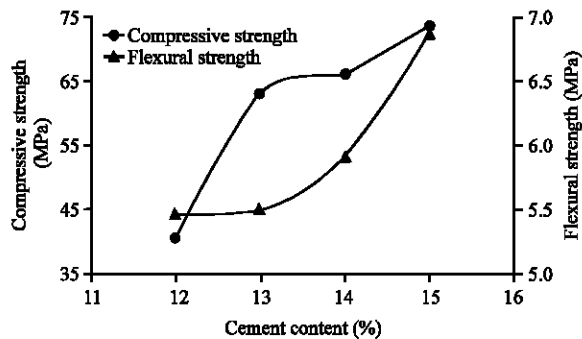Fig. 3: Relationship between OMC and cement content for RCC mixes

Fig. 4: Relationship between cement content and compressive/flexural strength

The samples were prepared and compacted according to ASTM C1435 using Bosch vibration hammer of 50 Hz frequency as shown in Fig. 5. The vebe consistency time for all mixes were determined according to ASTM C 1170 while the compressive strength for each mixes were determined after 7 and 28 days of curing using 100×100×100 mm cubes according to BS EN 12390-7:2009. Three samples were tested for each curing period and the average value was taken. The flexural strengths for each
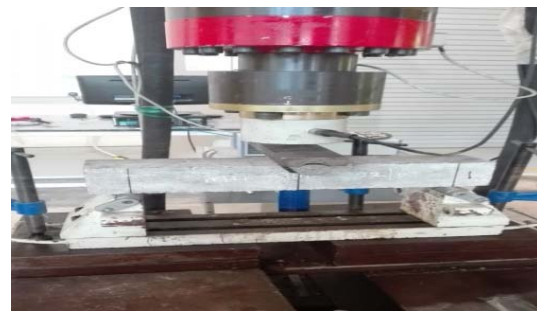

Fig. 5: Vibration hammer

Fig. 6: Flexural strength testing

mix was determined according to ASTM C293M-10 at 7 and 28 days after curing. Similarly, three samples were prepared and tested for each curing period. Figure 6 shows flexural strength sample testing.

RESULTS AND DISCUSSION

Vebe consistency: The results for the vebe consistency time for all mixes are shown in Fig. 7. It can be seen that partial replacement of fine aggregate with crumb rubber decreases the consistency time even without any addition of superplasticizer. The vebe time decreases by 3, 15.2 and 21.2% for 10, 20 and 30% replacement of fine aggregate with crumb rubber. This findings is similar to the findings by Meddah *et al.* (2014). The decrease in vebe time is

due to the lower water absorption properties of crumb rubber compared to fine aggregate, thus increasing the amount of free water during mixing and reducing the compaction time and effort needed (Meddah *et al.*, 2014). Addition of superplasticizer further decreases the consistency time of RCR. When 1% superplasticizer was added the water content was reduced by 12% and compared to RCR with 0% superplasticizer, the vebe time decreases by 6.1, 6.25, 10.7 and 7.7% for 0, 10, 20 and 30% crumb rubber, respectively. While for 2% superplasticizer addition the water content was reduced by 15% this leads to decrease in vebe time by 21.2, 18.8, 17.9 and 15.4% for 0, 10, 20 and 30% crumb rubber, respectively. The decrease in vebe time is due to the ability of superplasticizer to help in distribution and dispersion of the paste content. The mechanism for the decrease in vebe time of RCR is the paste which contains very fine cement and mineral filler (fly ash) cling together and flocculate during hydration process with water thereby entrapping some of the water available for mixing however, superplasticizer negative charge on the flocculated paste particles causing repulsion and consequently dispersion thus freeing the available water for mixing (Xu *et al.*, 2016).
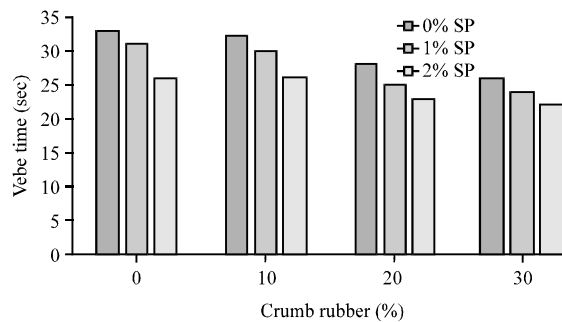

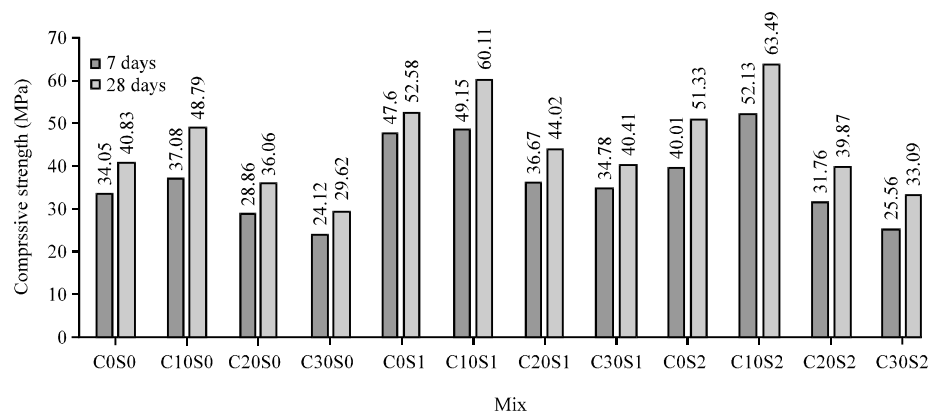Fig. 7: Vebe consistency time for RCR mixes

Compressive strength: The results of 7 and 28 days compressive strength for all RCR mixes for 0-2% superplasticizer is presented in Fig. 8. For all superplasticizer content partial replacement of fine aggregate with crumb rubber above 10% decreases the compressive strength at all age of curing. The 28 days compressive strength of RCR containing 0% superplasticizer decreases by 11.7 and 27.5% for 20 and 30% crumb rubber, respectively and increases by 19.5% for 10% crumb rubber. While for 1% superplasticizer, 28 days compressive strength decreases by 16.3 and 23.1% for 20 and 30% crumb rubber, respectively and increases by 14.3 for 10% crumb rubber. The reduction in compressive strength with crumb rubber addition is caused by the poor bonding between hardened cement matrix and rubber particles and increased pore volume in the hardened RCR mix which leads to micro crack formation with applied loads and consequently premature failure (Mohammed *et al.*, 2016; Thomas *et al.*, 2016). Another reason is due to lower elastic modulus, strength, stiffness and load carrying ability of crumb rubber in comparison to fine aggregate it partially replaced (Xue and Shinozuka, 2013). While the increase in compressive strength for 10% crumb rubber can be due to increased consistency by the crumb rubber allowing for proper compaction, hence leading to lower voids in the hardened RCR and increased strength. In addition, higher strengths were achieved due to the use of fly ash as mineral filler which contributed to strength development apart from filling ability due to its pozzolanic reaction. Higher compaction effort utilized also resulted to a more compacted hardened paste and hence increased strength.

Addition of superplasticizer increases the compressive strength of RCR. The 28 days compressive strength of RCR incorporating 1% superplasticizer increases by 28.8, 23.2, 22.1 and 36.4% for 0, 10, 20 and

Fig. 8: Compressive strength of RCR mixes

30% crumb rubber, respectively compared to RCR with 0% superplasticizer. While addition of 2% superplasticizer increases the 28 days compressive strength by 25.7, 30.1, 10.6 and 11.7% for 0, 10, 20 and 30% crumb rubber, respectively. It can be seen that 1% superplasticizer is the optimum dosage for RCR as it produces the highest strength values. The increase in strength with addition of superplasticizer is due to the reduced water/cement ratio which consequently increases strength. It is also due to the increase in consistency of RCR with superplasticizer addition which resulted to a high proper compaction, leading to reduced void content in the hardened RCR and consequently increased compressive strength.

The relationship between 28 days compressive strength and vebe consistency time for RCR incorporating 0, 1 and 2% superplasticizer is shown in Fig. 9. As seen there is a good correlation between the compressive strength and vebe time with RCR containing 2% superplasticizer having the best degree of correlation ($R^2 = 0.903$).

Flexural strength: The results of flexural strength of RCR with addition of 0, 1 and 2% superplasticizer is shown in Fig. 10. The flexural strength of RCR increases with partial
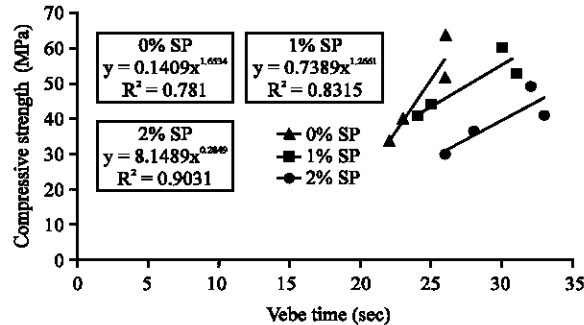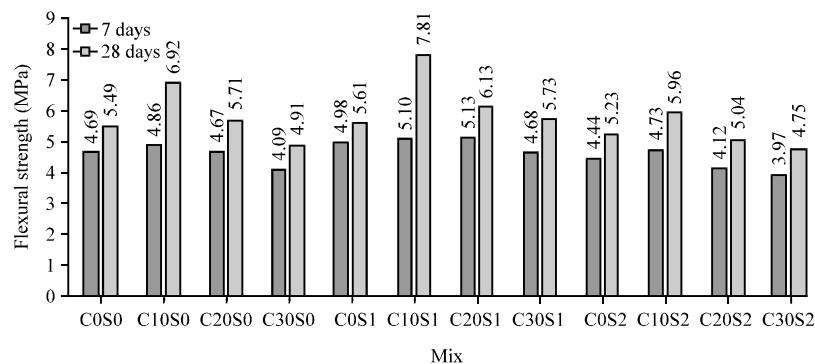
replacement of fine aggregate with crumb rubber for all superplasticizer content. The 28 days flexural strength of RCR with 0% superplasticizer increases by 26 and 4% for 10 and 20% crumb rubber, respectively and decreases by 10.6% for 30% crumb rubber. Similarly, for 1% superplasticizer, the flexural strength of RCR increases by 39.2, 9.3 and 2.1% for 10, 20 and 30% crumb rubber, respectively. This similar trend is observed for RCR with 2% superplasticizer as shown in Fig. 10. This findings was similar to results obtained (Yilmaz and Degirmenci, 2009). The increase in flexural strength is attributed to the high bending deformation and fiber nature of CR which gives the RCR post cracking behavior and allows it to resist some flexural load even after failure (Thomas and Gupta, 2015). While the decrease in flexural strength is due to poor bonding between crumb rubber and hardened cement paste causing premature flexural failure begins to occur.

Addition of superplasticizer has effect on the flexural strength of RCR but the effect is lower compared to compressive strength. For 1% superplasticizer addition, the 28 days flexural strength of RCR increases by 2.19, 12.86, 7.36 and 16.7% for 0, 10, 20 and 30% crumb rubber, respectively in comparison to RCR with 0% superplasticizer. However, for 2% superplasticizer addition, the flexural strength decreases by 4.7, 13.9, 11.7 and 3.3% for 0, 10, 20 and 30% crumb rubber, respectively compared to RCR with 0% superplasticizer. The increase in flexural strength with addition of superplasticizer is attributed to the reduction in water/cement ratio which results to increase in strength. It is also due to increased consistency and dispersion of paste with superplasticizer thus resulting to a more proper compaction to be achieved, leading to a denser RCR matrix and consequently increases bending resistance. While decrease in flexural strength with addition of superplasticizer is attributed to the extra water available after consistency has been achieved. After the fresh RCR

Fig. 9: Relationship between compressive strength and vebe time of RCR

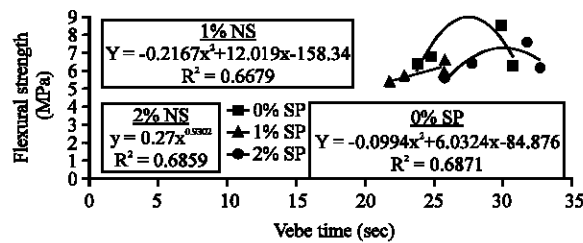Fig. 10: Flexural strength of RCR

Fig. 11: Relationship between flexural strength and vebe time of RCR

has dried the excess water also dried up leaving voids in the hardened RCR. Micro cracks forms along the voids when bending load is applied thus causing premature failure and reduction in flexural strength.

The relationship between flexural strength and vebe consistency time of RCR containing 0-2% superplasticizer is shown in Fig. 11. The degree of correlation between then is not high compared to that of compressive strength. This is to say the consistency of RCR has more effect on its compressive strength compared to flexural strength.

CONCLUSION

In this study, the effect of superplasticizer dosage on the vebe consistency time, compressive strength and flexural strength of roller compacted rubbercrete made by partial replacement of fine aggregate with crumb rubber at 0, 10, 20 and 30% in RCC pavement. Based on the experiment results and analysis the following conclusions can be drawn.

The compressive strength of RCR at all age of curing and for any percentage addition of superplasticizer decreases with increase in partial replacement of fine aggregate with crumb rubber above 10%. For 10% replacement level the compressive strength was found to increase.

The flexural strength of RCR for any superplasticizer addition increases with increase in partial replacement of fine aggregate with crumb rubber for up to 20% replacement level.

The compressive strength and flexural strength of RCR increases with addition of superplasticizer. However, flexural strength decreases when 2% superplasticizer was added. The vebe consistency time of RCR decreases with increase in partial replacement of fine aggregate with crumb rubber. It also decreases with increase in addition of superplasticizer. The vebe consistency of RCR has more effect on its compressive strength than flexural strength. The recommended optimum dosage for use in RCR is 1% by weight of cementitious materials.

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