



Received: 02 January 2018
Accepted: 30 January 2018
First Published: 02 February 2018

*Corresponding author: Bashar S. Mohammed, Department of Civil and Environmental Engineering, Universiti Teknologi Petronas, 32610 Bandar Seri Iskandar, Perak, Malaysia
E-mail: bashar.mohammed@utp.edu.my

Reviewing editor:
Paolo Zampieri, Università degli Studi di Padova, Italy

Additional information is available at the end of the article

CIVIL & ENVIRONMENTAL ENGINEERING | SHORT COMMUNICATION

Effect of crumb rubber and nano silica on the fatigue performance of roller compacted concrete pavement

Musa Adamu^{1,2}, Bashar S. Mohammed^{1*}, Nasir Shafiq¹ and Mohd Shahir Liew¹

Abstract: Roller compacted concrete (RCC) pavement is subjected to continues traf-
fic loading from vehicular activities which can results to fatigue cracking. Fatigue is
one of the commonest defects affecting pavement which affect the cost of mainte-
nance, and shortens pavement design life. To carter for these factors, higher defor-
mation resistant pavements with longer design life need to be designed. Therefore,
in this study, crumb rubber was used as a partial replacement to fine aggregate in
RCC pavement to improve its fatigue life. Five mixtures were considered; one control
mixture, two mixtures with fine aggregate replaced using crumb rubber at 10 and
20% by volume; one mixture containing 20% crumb rubber as partial replacement
to fine aggregate 1% nano silica added by weight of cementitious materials. Lastly,
one high volume fly ash (HVFA) RCC pavement mixture where 50% cement was re-
placed with fly ash, and 20% fine aggregate replaced with crumb rubber. The results
showed that both crumb rubber and nano silica increases the bending resistance
and fatigue life of RCC pavement. While HVFA decreases both flexural strength and
fatigue performance of RCC pavement. The double logarithmic-equation can best be
used to determine the stress level–number of cycles ($S-N$) fatigue behavior and rela-
tion for RCC pavement mixtures.

ABOUT THE AUTHORS

Musa Adamu is currently undergoing his PhD in Civil Engineering at Universiti Teknologi Petronas (UTP) Malaysia. His specialization is materials and structural engineering, and his current research is utilization of crumb rubber and nano silica in roller compacted concrete pavement.

Bashar S. Mohammed obtained his PhD in Structural Engineering at the Universiti Sains Malaysia. He is currently an Associate Professor and Head of Civil Engineering Department, UTP Malaysia. He has been involved in teaching and research for the past 15 years. His current research interest is development of rubbercrete.

Nasir Shafiq and Mohd Shahir Liew are currently Professors at the Department of Civil Engineering, UTP Malaysia. They have been involved in teaching and research for over 30 years. Nasir Shafiq area of research interest includes building information modeling, low carbon materials design and construction, and structural and materials engineering. Shahir Liew area of research interest is structural dynamics, and offshore engineering structures.

PUBLIC INTEREST STATEMENT

The major problem of RCC pavement is high rigidity and lower tensile strength. This causes high tendency of cracking due to flexural and fatigue loading. Furthermore, due to the way RCC pavement is placed and compacted, dowel bars, tie rod or steel reinforcement cannot be used. Therefore any applied load is resisted by the concrete action alone and transferred to the lower courses through aggregate interlock. Due to continuous traffic loads on the RCC pavement, there is high possibility of failure of the pavement without reaching its service life and increases the cost of maintenance. Therefore, to improve the fatigue performance of RCC pavement, crumb rubber was used as partial replacement to fine aggregate due to its high elastic and deformation properties. Nano silica was added to mitigate the loss in strength with incorporation of crumb rubber into RCC pavement.

Subjects: Composites; Concrete & Cement; Structural Engineering; Pavement Engineering

Keywords: crumb rubber; nano silica; S-N curve; roller compacted concrete pavement; fatigue; flexural strength

1. Introduction

According to ACI committee 207, “Roller-compacted concrete (RCC) is a concrete of no slump consistency in its unhardened state that is transported, placed and compacted using earth and rock fill construction equipment. Properties of hardened RCC are similar to those of conventional concrete” (American Concrete Institute, 207). In another word, RCC can be said to be a Roller compacted concrete differs from conventional concrete due to its consistency requirements and compaction effort needed, with lower water content, lower paste content, higher fine aggregate content, no entrained air (Mehta & Monteiro, 2006). The major advantages of RCC over conventionally placed concrete include high construction speed, reduced construction cost (Mohammed, Adamu, & Shafiq, 2017). RCC is used for pavement and dams applications (Adaska, 2006).

RCC pavement is subjected to flexural strength and repetitive cyclic loadings throughout its design life from moving vehicles. Fatigue is one of the commonest defects affecting pavement which affect the cost of maintenance and shortens pavement design life. It is, therefore, necessary to devise a means of reducing the fatigue effect by delaying the pavement deterioration and improving its design life. This is possible by incorporating additives such as polymers or fibers into the pavement mix where it absorbs the deformations and strains energy caused by heavy traffic (Moghaddam, Karim, & Abdelaziz, 2011).

The Fatigue performance of many civil engineering structures are very important as they are subjected to continuous traffic loading throughout their lifespan. Example of such structures includes steel railway bridges and road pavements (Paolo et al., 2017). RCC pavement is an important property of concern, since dowel bars, steel reinforcement or tie rods cannot be used in RCC pavement due to the way it is placed and consolidated. Meaning any load and its effect such as fatigue and flexural stresses are resisted by the concrete action alone and transferred through aggregate interlock to bottom layers (Mohammed, Adamu, & Liew, 2018). The method of testing fatigue in concrete is generally very tedious, expensive and time-consuming to accomplish (Zhou, Zheng, Wang, Yang, & Lin, 2016). Pavement fatigue design life is affected by several factors such as the type and content of the binder of the mixture used, air voids and temperature of the mix (Moghaddam et al., 2011), aggregate type and gradation also have effect on fatigue life of pavement, larger aggregate gradation gives the worse fatigue life i.e. the larger the NMSA, the lower the fatigue life (Abo-Qudais & Shatnawi, 2007).

Very scarce literature is available on the fatigue performance of RCC pavement. Sun et al. (1998), studied the fatigue performance of fly ash RCC pavement at different stress ratios, they partially replaced cement with fly ash at 0, 15, 30, and 45%. They found that RCC exhibits excellent fatigue performance compared to conventional concrete pavement. They also found that fly ash increases the fatigue performance of RCC pavement by up to 50%. This was due to micro-aggregate effect and pozzolanic reactivity of fly ash. Graeff, Pilakoutas, Neocleous, and Peres (2012), studied the effect of fibers on the fatigue performance of RCC pavement. They added 2% of 1 mm cold drawn wire with a cone forged at each end, and 2 and 6% fiber recovered from mechanical treatment of post-consumer tires, by mass of RCC. They tested the fatigue at 0.5, 0.7 and 0.9 stress levels. Both fibers increase the fatigue life of RCC, with 2% fiber content been optimum. However, this was true for up to 0.7 stress levels. Above 0.7 stress levels, RCC without fibers has better fatigue performance which is due to better aggregate interlocks. They concluded that the combination of both types of fibers will give better fatigue life than using single fiber type due to; fiber from post-consumer tires has better effectiveness in the restraining propagation of micro-cracks to meso-cracks, while fibers from cold drawn wires have the better efficiency to hold macro-cracks together. Sobhan, Gonzalez, and Reddy (2016), studied the fatigue performance of RCC pavement base course made with recycled

aggregate in wet and dry conditions. Their findings showed that RCC pavement base course in wet condition has lower fatigue strength and residual compressive/flexural strength compared to in dry condition. They also reported that recycled aggregates are good alternative materials to RCC pavement base course. Sobhan and Das (2007), also studied the fatigue performance of soil-cement for pavement lower bases, made with stabilized recycled aggregate (SRA) containing cement and fly ash mixtures. They found that the fatigue performance of SRA is similar or higher than that of other traditional cementitious composites.

To the best knowledge of the authors, there is limited or no available literature that studied the effect of hybrid of crumb rubber and nano silica on the fatigue performance of RCC pavement. Therefore, this study is aimed at studying the fatigue performance of RCC pavement.

2. Materials and methods

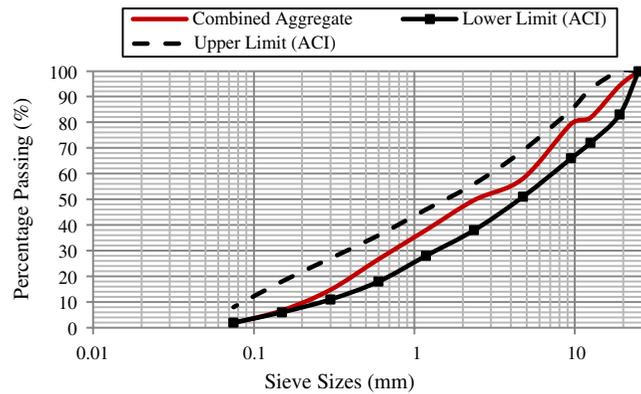
2.1. Materials

Type I ordinary Portland cement which conforms to the requirements of ASTM C150 was used. Class F fly ash conforming the requirements of ASTM C612 was used as supplementary cementitious materials (SCM). Natural sand was used as a fine aggregate with a maximum size of 4.75 mm, specific gravity 2.65, fineness modulus 2.86 and water absorption of 1.24%. Two nominal maximum sizes of coarse aggregates have been used to achieve the desired combined aggregate gradation. These are 19 mm size having a specific gravity of 2.66 and water absorption of 0.48% and 6.35 mm size having a specific gravity of 2.55 and water absorption of 1.05%. Three different crumb rubber sizes have been combined to obtain similar gradation curve to fine aggregate. Therefore combinations of 40% mesh 30 (0.595 mm), 40% of 1–3 mm and 20% of 3–5 mm have been selected. Strong hydrophobic nano silica size 10–25 nm has been used as an additive to the cement. The nano-silica is amorphous in nature; therefore, it will act as both filler and pozzolanic material. One of the requirements for RCC pavement mixture production is using materials finer than 75 μm (No 200 sieve) to achieve a more cohesive paste with reduced void volume. The recommended amount should be between 2 to 8% of the total aggregates (Adamu, Mohammed, & Shafiq, 2017; Mohammed & Adamu, 2018a). In this study, the same class F fly ash used as SCM was used as mineral filler.

2.2. Mix design and proportioning

Mix proportioning has been carried out according to the geotechnical approach to the requirements of ACI 211.3R-02 (A. Lazaro). Firstly, the combined aggregate gradation of fine and coarse aggregate to be within the limits recommended by ACI 325.10R and ACI 211.3R was determined. After several series of trials, a combination of 55% fine aggregate, 20% of 19 mm maximum sized coarse aggregate, 20% of 6.3 mm coarse aggregate and 5% mineral filler has been selected and the combined aggregate gradation is plotted as shown in Figure 1. The optimum moisture contents and maximum dry densities for RCC mix with 12, 13, 14 and 15% by weight of dry aggregate have been determined according to the requirements of ASTM D 1557-12e. The optimum moisture content for RCC with 12, 13, 14 and 15% cement has been found to be 5.46, 5.56, 5.92 and 6.09%, respectively. Subsequently, the relationship between cement content and flexural strength was determined, this has been done by producing four RCC mixes with 12, 13, 14 and 15% cement content and water content equal to their OMC and then tested for flexural strengths at age of 28 days. Based on target flexural strength of 4.8 MPa, 13% cement content has been selected to be used in this study. A water/cement ratio of 0.42 has been established based on the quantities of the selected materials. To reduce the water content and increase consistency, 1% superplasticizer by weight of cementitious materials was added and the water content has been reduced by 12%, bringing the water/cement ratio down to 0.37.

Figure 1. Combined aggregate gradation.



2.3. Sample preparations and experimental programs

2.3.1. Mix composition

In this study, five mixtures were prepared. They are one control mixture, two mixtures with fine aggregate replaced using crumb rubber at 10 and 20% by volume; one mixture containing 20% crumb rubber as partial replacement to fine aggregate 1% nano silica added by weight of cementitious materials. Lastly, one high volume fly ash (HVFA) RCC pavement mixture where 50% cement was replaced with fly ash, and 20% fine aggregate replaced with crumb rubber. Each mix was assigned a designation code based on fly ash, crumb rubber and nano silica used, for example, M10CON refers to RCC mixture with 10% of crumb rubber and 0% nano silica, M20C50FON is an RCC mixture with 20% crumb rubber, 50% HVFA and 0% of nano-silica. RCC mix proportions are shown in Table 1.

2.3.2. Test Procedures

In order to simulate roller compaction, and achieve a fully consolidated RCC mixture, vibration hammer of 50 Hz capacity was used to compact the RCC samples, which is in accordance to the requirements of ASTM C1435. Full compaction was achieved when ring of mortar forms across the periphery of the base plate.

In this study, the flexural strength test has been performed in accordance with ASTM C293 using a simple beam with center point loads. The test was conducted using self-straining loading frame attached to a 500 kN capacity dynamic servo-controlled actuator as shown in Figure 2. For each mixture, two beams of 100 mm × 100 mm × 500 mm were prepared and used for the testing, the average value then recorded. The loading was applied at a speed of 0.1 mm/s. The test performed after 28 days curing period in water at a temperature of 23 °C.

The fatigue test is used to determine the number of cycles of repetitive loads the RCC will resist without failure at a specific stress ratio. Beams of 100 mm × 100 mm × 500 mm sizes were prepared and cured in water for 28 days prior to testing. The fatigue test has been carried in a similar way to

Table 1. Mix proportioning

Mixtures	Cement (kg/m ³)	Fly Ash (kg/m ³)	Nano silica (kg/m ³)	Filler (kg/m ³)	Fine aggregate (kg/m ³)	Coarse aggregate -19 mm (kg/m ³)	Coarse aggregate -6.35 mm (kg/m ³)	Water (kg/m ³)	Crumb rubber (kg/m ³)
MOCON	268.69	0	0	103.76	1,148.05	415.03	416.85	98.24	0
M10CON	268.69	0	0	103.76	1,033.25	415.03	416.85	98.24	114.89
M20CON	268.69	0	0	103.76	918.44	415.03	416.85	98.24	229.78
M20C1N	268.69	0	2.69	103.94	918.44	415.03	416.85	98.24	229.78
M20C50FON	134.58	102.54	0	103.94	920.06	415.76	417.58	96.87	230.17

Figure 2. Flexural strength testing.



flexural strength using three points load. Self-straining loading frame attached to a 500 kN capacity dynamic servo-controlled actuator was used for testing. The maximum static flexural loads (f_r) obtained from the flexural test results of each mix was used for evaluating the repetitive loads. The fatigue test was conducted at three stress levels ($S = f_{max}/f_r$) i.e. 0.7, 0.8 and 0.9 due to the fact that at lower stress levels the specimens will reach their limits without failing, and at very high-stress levels the specimens will fail at few cycles. The maximum load (f_{max}) to be applied to each specimen for the fatigue test was calculated from the static flexural load (f_r) and the stress levels. A constant fatigue stress ratio ($R = f_{max}/f_{min}$) was kept constant to 0.1 throughout the fatigue testing due to the fact that the minimum sustainable stress on pavement cannot be zero. The minimum load (f_{min}) to be applied on each specimen in the fatigue test was calculated from the maximum fatigue load (f_{max}) and the stress ratio R. The loading parameter for each mix/stress level is shown in Table 2. The fatigue test was terminated as soon as the specimen fails or reaches 2 million cycles without failure, and the number of cycles was recorded.

Table 2. Loading parameters for fatigue testing

Mixture	Ultimate bending resistance (kN)	Stress level S					
		0.7		0.8		0.9	
		f_{max} (MPa)	f_{min} (MPa)	f_{max} (MPa)	f_{min} (MPa)	f_{max} (MPa)	f_{min} (MPa)
MOCON	9.35	6.55	0.65	7.48	0.75	8.42	0.84
M10CON	13.01	9.11	0.91	10.41	1.04	11.71	1.17
M20CON	10.21	7.15	0.71	8.17	0.82	9.19	0.92
M20C1N	10.83	7.58	0.76	8.66	0.87	9.75	0.97
M20C50FON	7.32	5.12	0.51	5.86	0.59	6.59	0.66

3. Results and discussion

3.1. Flexural strength

The result of the 28 days flexural strengths are shown in Figure 3. The flexural strengths of RCC pavement mixtures without incorporation of HVFA increase when crumb rubber (CR) replaced fine aggregate. The flexural strength of M10CON and M20CON were higher than the control (M0CON) by 39.2 and 9.3% respectively. These results were in agreement with the findings of Yilmaz and Degirmenci (2009) for using crumb rubber in conventional concrete, and Fakhri (2016) for RCC pavement incorporating crumb rubber. The increase in flexural strength is attributed to the high bending deformation and fiber nature of CR, which gives the RCC post-cracking behavior and allows it to resist some flexural load even after failure (Thomas & Gupta, 2015). On the other hand, partial replacement of cement with HVFA decreases its flexural strength. The flexural strength of M20C50F0N was lower than that of M0CON by 21.7%. This decrease can be attributed to a combination of two factors; poor bonding between cement paste and crumb rubber, thus increasing the weakness points, causing failure to occur with application of bending loads (Mohammed & Azmi, 2014; Mohammed et al., 2017), and slower pozzolanic reactivity of fly ash at early ages which causes lower calcium-silicate-hydrate development, thus leading to reduction in bending resistance (Lv, Zhou, Du, & Wu, 2015). The addition of 1% nano silica increases the flexural strength of RCC pavement. The flexural strength of M20C1N was higher by 15.9 and 6.0% compared to M0CON and M20CON respectively. This increase is attributed to the strengthening and densification of the ITZ between crumb rubber-cement paste and aggregate-cement paste due to the increased pozzolanic reaction by NS (Mukharjee & Barai, 2014).

Figure 3. Flexural strength of RCC pavement.

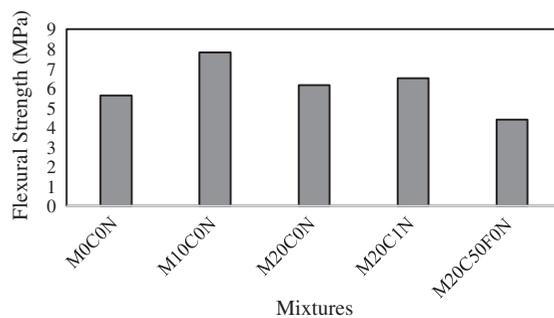


Table 3. Fatigue cycles for selected RCC mixtures

Mixture	Samples	Stress ratios/Number of cycles		
		0.7	0.8	0.9
M0CON	1	123,209	71,874	1,364
	2	110,433	65,481	866
M10CON	1	191,464	115,896	2,173
	2	142,695	61,064	9,146
M20CON	1	386,004	200,426	23,548
	2	273,926	177,652	14,955
M20C1N	1	468,263	264,197	42,562
	2	223,496	129,365	2,221
M20C50F0N	1	328,469	197,355	17,172
	2	194,632	110,469	3,464

3.2. Fatigue

The number of cycles (N) required causing fatigue failure at different stress ratios for the RCC mixtures is given in Table 3. For each mixture/stress levels, two samples have been tested, and the best results were chosen for analysis and result interpretation. The fatigue results exhibit wide variations and discreteness with one another. This can be attributed to the composite nature and inhomogeneity in the RCC mixtures which resulted to dissimilar fatigue lives for each mixture under the same stress levels (Liu, Meng, Ning, & Li, 2015). The fatigue life of RCC decreases with increase in stress levels, i.e. higher fatigue lives were achieved at the lower stress levels. Furthermore, it can be observed that at the same stress levels, the fatigue lives (the number of cycles) of RCC increases with increase in partial replacement of fine aggregate with crumb rubber. For example, the highest fatigue life was achieved for M20C0N at 0.7 stress level. This increase can be attributed to the high elastic, deformation and fiber nature of crumb rubber, which makes it act as a micro spring in the RCC mixtures, thereby decreasing its flexural elasticity, absorbing strain energy from the cyclic loads through deformation, delaying crack initiation time, and bridging micro-cracks under cyclic loadings thereby increasing its fatigue life (Liu et al., 2015).

The addition of nano silica increases the fatigue life of RCC at the same stress level. It can be observed from Table 3, at the same stress levels the number of cycles required to cause fatigue failure for mixture M20C1N were higher compared to that of M20C0N and M0C0N. Nano silica increases cement hydration and contributes in the pozzolanic reaction in RCC, this in addition to its filler nature helps in densifying the interfacial transition zone between cement paste and rubber particles, makes the hardened cement paste denser and compact by decreasing its porosity (Mohammed & Adamu, 2018b; Mohammed, Awang, San Wong, & Nhavene, 2016). This leads to increase in fatigue life of RCC pavement as fatigue failure occurs by initiating micro-cracks through the weak zones (pores) in the hardened cement matrix which later propagates to macro-cracks (Aggarwal, Singh, & Aggarwal, 2015; Li, Zhang, & Ou, 2007).

The fatigue life of RCC pavement decreases with partial replacement of cement with HVFA. For example, the fatigue number of M20C50F0N was found to be lower than that of M20C0N and M0C0N at the same stress levels. This decrease can be attributed to the reduction in cement hydration and the slower pozzolanic reaction of fly ash at an early age which resulted to higher porosity in the hardened RCC mixtures, thus increasing the tendency of micro-cracks initiation with the application of cyclic loads which leads to lower fatigue life (Sun et al., 1998). However, Yoo, Ryu, and Choo (2015) reported that the fatigue life of reinforced concrete beams increases when 50% high volume fly ash was used as cement replacement and tested at longer age.

The Wohler curve or $S-N$ curve can be used to obtain the relationship between the stress levels (S) and the number of cycles for fatigue failure (N). However, the major setback of the $S-N$ method is that it does not include the degradation state of the RCC pavement under fatigue loading (Paolo, Curtarello, Maiorana, & Pellegrino, 2017; Zampieri, Curtarello, Pellegrino, & Maiorana, 2018). The generalized fatigue $S-N$ relationships as recommended by several researchers is either the single logarithmic function shown in Equation (1) or double logarithmic function as given in Equation (2) (Liu et al., 2015).

$$S = x - y \times \text{Log}(N) \quad (1)$$

$$\text{Log}(S) = x - y \times \text{Log}(N) \quad (2)$$

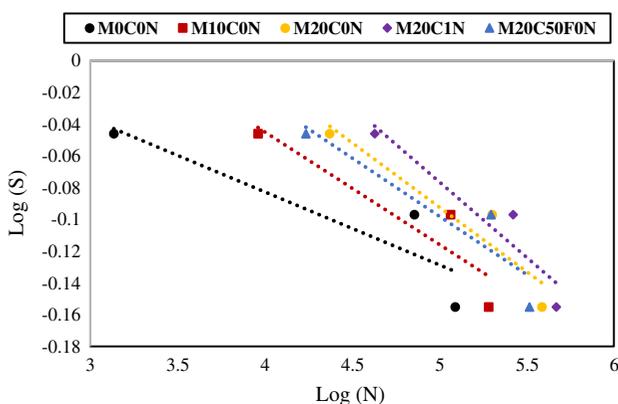
where S is the stress levels, N is the number of cycles, x and y are the regression coefficients which reflects the height and steepness of the $S-N$ curve respectively.

The choice of either the single logarithmic or the double logarithmic equations to represent the fatigue $S-N$ behavior of a material depends on the ranges of stress levels (S) used. For a range ($0.55 < S < 0.85$), then the single logarithmic equation is best used and cannot extend, while for S

Table 4. Relationship between stress level and number of cycles (S–N) fatigue for RCC

Mixtures	Relationship between Log(S) and Log(N)	R ²
M0C0N	$\text{Log}(S) = 0.1016 - 0.046\text{Log}(N)$	0.811
M10C0N	$\text{Log}(S) = 0.2388 - 0.0706\text{Log}(N)$	0.845
M20C0N	$\text{Log}(S) = 0.314 - 0.0812\text{Log}(N)$	0.893
M20C1N	$\text{Log}(S) = 0.3987 - 0.095\text{Log}(N)$	0.90
M20C50F0N	$\text{Log}(S) = 0.2694 - 0.0735\text{Log}(N)$	0.85

Figure 4. S–N fatigue curves for RCC mixtures.



values outside this range, the double logarithmic function is the best recommended (Li et al., 2007). Therefore the double logarithmic equations were used to develop the S–N relationships and S–N curves of RCC mixtures as shown in Table 4 and Figure 4 respectively. The developed S–N relationships have a high degree of correlations ($R^2 > 0.8$), with RCC mixture M10C0N having the best correlation. Therefore, the double logarithmic function can be used to develop the S–N fatigue relationship for RCC mixtures. By comparing the developed relationships in Table 3 and Equation (2), it can be seen that mixture M20C1N has the highest x-coefficient (0.3987) and y-coefficient (0.095) which implies it has the highest fatigue life and is more sensitive to change in stress respectively compared to the other mixtures. While mixture M0C0N has the lowest x-coefficient (0.1016) and lowest y-coefficient (0.046), therefore it has the lowest fatigue life and sensitivity to change in stress respectively (Li et al., 2007). This can be verified by observing Figure 4, the curve for M20C1N is the highest and the steepest while that of M0C0N is the lowest and the mildest.

4. Conclusions

The following conclusions can be drawn based on the experimental works and results analysis carried out.

- The flexural strength of RCC pavement increased with the replacement of up to 20% fine aggregate with crumb rubber and the addition of nano-silica. However, HVFA decreases the flexural strength of RCC pavement
- The fatigue performance of RCC pavement increases with partial replacement of fine aggregate with crumb rubber and the addition of nano-silica. However, the use of HVFA decreases the fatigue performance of RCC pavement.
- The developed double logarithmic-equation of the S–N fatigue curve for RCC pavement mixtures has a good degree of correlation

Funding

This work was supported by the Ministry of Higher Education (MOHE) of Malaysia [project number PRGS/1/13/TK03/UTP/02/02].

Author details

Musa Adamu^{1,2}

E-mail: musa.adamu_g03310@utp.edu.my

ORCID ID: <http://orcid.org/0000-0001-9674-479X>

Bashar S. Mohammed¹

E-mail: bashar.mohammed@utp.edu.my

Nasir Shafiq¹

E-mail: nasirshafiq@utp.edu.my

Mohd Shahir Liew¹

E-mail: shahir_liew@utp.edu.my

¹ Department of Civil and Environmental Engineering, Universiti Teknologi Petronas, 32610 Bandar Seri Iskandar, Perak, Malaysia.

² Department of Civil Engineering, Bayero University, PMB 3011 Kano, Nigeria.

Citation information

Cite this article as: Effect of crumb rubber and nano silica on the fatigue performance of roller compacted concrete pavement, Musa Adamu, Bashar S. Mohammed, Nasir Shafiq & Mohd Shahir Liew, *Cogent Engineering* (2018), 5: 1436027.

References

- Abo-Qudais, S., & Shatnawi, I. (2007). Prediction of bituminous mixture fatigue life based on accumulated strain. *Construction and Building Materials*, 21(6), 1370–1376. <https://doi.org/10.1016/j.conbuildmat.2005.09.004>
- Adamu, M., Mohammed, B. S., & Shafiq, N. (2017). Mechanical performance of roller compacted rubbercrete with different mineral fillers. *Jurnal Teknologi*, 79(6), 75–88.
- Adaska, W. S. (2006). *Roller-compacted concrete (RCC). Significance of Tests and Properties of Concrete and Concrete-making Materials* (p. 595). West Conshohocken, PA: ASTM International.
- Aggarwal, P., Singh, R. P., & Aggarwal, Y. (2015). Use of nano-silica in cement based materials – A review. *Cogent Engineering*, 2(1), 1078018.
- American Concrete Institute. (2017). *Roller compacted mass concrete materials journal* (Vol. 85). Michigan, IN: American Concrete Institute.
- Fakhri, M. (2016). The effect of waste rubber particles and silica fume on the mechanical properties of roller compacted concrete pavement. *Journal of Cleaner Production*, 129, 521–530. <https://doi.org/10.1016/j.jclepro.2016.04.017>
- Graeff, A. G., Pilakoutas, K., Neocleous, K., & Peres, M. V. N. (2012). Fatigue resistance and cracking mechanism of concrete pavements reinforced with recycled steel fibres recovered from post-consumer tyres. *Engineering Structures*, 45, 385–395. <https://doi.org/10.1016/j.engstruct.2012.06.030>
- Li, H., Zhang, M.-H., & Ou, J.-P. (2007). Flexural fatigue performance of concrete containing nano-particles for pavement. *International Journal of Fatigue*, 29(7), 1292–1301. <https://doi.org/10.1016/j.ijfatigue.2006.10.004>
- Liu, F., Meng, L.-Y., Ning, G.-F., & Li, L.-J. (2015). Fatigue performance of rubber-modified recycled aggregate concrete (RRAC) for pavement. *Construction and Building Materials*, 95, 207–217. <https://doi.org/10.1016/j.conbuildmat.2015.07.042>
- Lv, J., Zhou, T., Du, Q., & Wu, H. (2015). Effects of rubber particles on mechanical properties of lightweight aggregate concrete. *Construction and Building Materials*, 91, 145–149. <https://doi.org/10.1016/j.conbuildmat.2015.05.038>
- Mehta, P. K., & Monteiro, P. J. (2006). *Concrete: Microstructure, properties, and materials* (Vol. 3). New York, NY: McGraw-Hill.
- Moghaddam, T. B., Karim, M. R., & Abdelaziz, M. (2011). A review on fatigue and rutting performance of asphalt mixes. *Scientific Research and Essays*, 6(4), 670–682.
- Mohammed, B. S., & Adamu, M. (2018a). Mechanical performance of roller compacted concrete pavement containing crumb rubber and nano silica. *Construction and Building Materials*, 159, 234–251. doi:doi: 10.1016/j.conbuildmat.2017.10.098
- Mohammed, B. S., & Adamu, M. (2018b). Non-destructive evaluation of nano silica-modified roller-compacted rubbercrete using combined SonReb and response surface methodology. *Road Materials and Pavement Design*, 1–21. doi:10.1080/14680629.2017.1417891
- Mohammed, B. S., Adamu, M., & Liew, M. S. (2018). Evaluating the static and dynamic modulus of elasticity of roller compacted rubbercrete using response surface methodology. *International Journal*, 14(41), 186–192.
- Mohammed, B. S., Adamu, M., & Shafiq, N. (2017). A review on the effect of crumb rubber on the properties of rubbercrete. *International Journal of Civil Engineering and Technology*, 8(9), 599–615. <https://doi.org/10.1007/s40999-017-0190-y>
- Mohammed, B. S., Awang, A. B., San Wong, S., & Nhavene, C. P. (2016). Properties of nano silica modified rubbercrete. *Journal of Cleaner Production*, 119, 66–75. <https://doi.org/10.1016/j.jclepro.2016.02.007>
- Mohammed, B. S., & Azmi, N. (2014). Strength reduction factors for structural rubbercrete. *Frontiers of Structural and Civil Engineering*, 8(3), 270–281. <https://doi.org/10.1007/s11709-014-0265-7>
- Mukharjee, B. B., & Barai, S. V. (2014). Influence of nano-silica on the properties of recycled aggregate concrete. *Construction and Building Materials*, 55, 29–37. <https://doi.org/10.1016/j.conbuildmat.2014.01.003>
- Paolo, Z., Curtarello, A., Maiorana, E., & Pellegrino, C. (2017). Numerical analyses of corroded bolted connections. *Procedia Structural Integrity*, 5, 592–599. <https://doi.org/10.1016/j.prostr.2017.07.020>
- Paolo, Z., Curtarello, A., Maiorana, E., Pellegrino, C., De Rossi, N., Savio, G., & Concheri, G. (2017). Influence of corrosion morphology on the Fatigue strength of Bolted joints. *Procedia Structural Integrity*, 5, 409–415. <https://doi.org/10.1016/j.prostr.2017.07.189>
- Sobhan, K., & Das, B. M. (2007). Durability of soil-cements against fatigue fracture. *Journal of Materials in Civil Engineering*, 19(1), 26–32. [https://doi.org/10.1061/\(ASCE\)0899-1561\(2007\)19:1\(26\)](https://doi.org/10.1061/(ASCE)0899-1561(2007)19:1(26))
- Sobhan, K., Gonzalez, L., & Reddy, D. (2016). Durability of a pavement foundation made from recycled aggregate concrete subjected to cyclic wet-dry exposure and fatigue loading. *Materials and Structures*, 49(6), 2271–2284. <https://doi.org/10.1617/s11527-015-0648-9>
- Sun, W., Liu, J., Qin, H., Zhang, Y., Jin, Z., & Qian, M. (1998). Fatigue performance and equations of roller compacted concrete with fly ash. *Cement and Concrete Research*, 28(2), 309–315. [https://doi.org/10.1016/S0008-8846\(97\)00211-1](https://doi.org/10.1016/S0008-8846(97)00211-1)
- Thomas, B. S., & Gupta, R. C. (2015). Properties of high strength concrete containing scrap tire rubber. *Journal of Cleaner Production*, 113, 86–92.
- Yilmaz, A., & Degirmenci, N. (2009). Possibility of using waste tire rubber and fly ash with Portland cement as construction materials. *Waste Management*, 29(5), 1541–1546. <https://doi.org/10.1016/j.wasman.2008.11.002>

Yoo, S.-W., Ryu, G.-S., & Choo, J. F. (2015). Evaluation of the effects of high-volume fly ash on the flexural behavior of reinforced concrete beams. *Construction and Building Materials*, 93, 1132–1144. <https://doi.org/10.1016/j.conbuildmat.2015.05.021>

Zampieri, P., Curtarello, A., Pellegrino, C., & Maiorana, E. (2018). Fatigue strength of corroded bolted connection. *Frattura ed Integrità Strutturale*, 12(43), 90–96.

Zhou, J., Zheng, M., Wang, Q., Yang, J., & Lin, T. (2016). Flexural fatigue behavior of polymer-modified pervious concrete with single sized aggregates. *Construction and Building Materials*, 124, 897–905. <https://doi.org/10.1016/j.conbuildmat.2016.07.136>



© 2018 The Author(s). This open access article is distributed under a Creative Commons Attribution (CC-BY) 4.0 license.

You are free to:

Share — copy and redistribute the material in any medium or format

Adapt — remix, transform, and build upon the material for any purpose, even commercially.

The licensor cannot revoke these freedoms as long as you follow the license terms.

Under the following terms:

Attribution — You must give appropriate credit, provide a link to the license, and indicate if changes were made.

You may do so in any reasonable manner, but not in any way that suggests the licensor endorses you or your use.

No additional restrictions

You may not apply legal terms or technological measures that legally restrict others from doing anything the license permits.



Cogent Engineering (ISSN: 2331-1916) is published by Cogent OA, part of Taylor & Francis Group.

Publishing with Cogent OA ensures:

- Immediate, universal access to your article on publication
- High visibility and discoverability via the Cogent OA website as well as Taylor & Francis Online
- Download and citation statistics for your article
- Rapid online publication
- Input from, and dialog with, expert editors and editorial boards
- Retention of full copyright of your article
- Guaranteed legacy preservation of your article
- Discounts and waivers for authors in developing regions

Submit your manuscript to a Cogent OA journal at www.CogentOA.com

