Tribological, Mechanical and Physical Properties of Concrete with Rubber Particles

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***Abstract*– Rubber particles in the form of crumb and shredded rubber have been considered for use in concrete as artificial aggregate. Several investigations have been conducted by previous researchers but most have not conducted comparative studies between shredded and crumb rubber and hence the effects that each type of rubber has on concrete have been investigated in this research. The results of this research show that the use of shredded and crumb rubber as fine aggregate replacement in traditional concrete reduces compressive and flexural strength of concrete and the propensity for water absorption. While the crumb rubber did not increase the impact resistance of concrete, the shredded rubber significantly delays crack initiation and failure from impact forces. Resistance to wear was increased, especially with the crumb rubber.**

***Keywords*-- abrasion, absorption, compression, tensile, impact.**

I. Introduction

Jamaica, like many other countries in the world, has serious problems with the huge pile of rubber tyres that are stored at the landfills. The deposit of this type of solid waste at the landfill has resulted in a significant overload of the space allocated for landfills in the main city of the island. As the decomposition of this type of waste will take 50 to 80 years, the accumulation of the rubber tyres poses a challenge to the national solid waste management agency. Further, the rubber tyres are a constant source of conflagration at the landfill and, generally, the tyres serve as a breeding ground for vectors. These and many other hazardous situations [1] at the waste tyre landfills present serious threats to the environment. Recently, private individuals in the Island have embarked on a project that seeks to pulverize the rubber tyre and use the resulting material for recycling purposes.

There are several studies in which rubber particles are used to produce rubberized asphaltic concrete (RAC). There are also investigative studies using rubber in concrete, often referred to as rubberized concrete. As the discussion promoting rubber in concrete is advanced, it appears as if the advent of rubberized concrete roads is imminent and this could be a consideration for the local investors.

The rubber from tyres can be processed by several methods to obtain rubber particles. Existing literature has shown that there are several ways to produce the rubber particles and the two main types of rubber particles seem to be crumb rubber and shredded rubber particles. For this research, comparative study will be undertaken on the two main rubber particles of interest. Therefore, this study will be on crumb rubber as well as shredded rubber in a cementitious medium, with the intention that the concrete will be used for pavement purposes. An investigation of the relative properties of crumb and shredded rubber will be conducted with a view to determine how each will affect concrete. Several previous studies have already been undertaken by researchers albeit the majority of them were limited to the investigation of some of the physical and mechanical properties of concrete. In 2004, three professors [2] from the Arizona State University conducted compressive strength and three-point flexural strength tests on crumb rubber concrete. The strength of the concrete was reduced with the inclusion of rubber. This research is therefore undertaken in order to achieve a better understanding of the behaviour of rubberized concrete and to gain deeper knowledge on the relative effects of crumb and shredded rubber particles on concrete.

Digital Object Identifier (DOI):
http://dx.doi.org/10.18687/LACCEI2019.1.1.496
ISBN: 978-0-9993443-6-1 ISSN: 2414-6390

The concrete will be designed with a compressive strength of approximately 21 MPa as it will be utilized as road pavement. Properties of the concrete that are integral to the performance of concrete will be investigated. These include physical test, mechanical test, and more pertinently, tribological test.

II. EXPERIMENTAL DESIGN

A. Materials

The cement used was Type 1, Portland Pozzolan cement of JS 301 type PP [3].

Four types of aggregate were used in the design of the concrete mixes, namely, coarse aggregate, sand, crumb rubber and shredded rubber. A sieve analysis was conducted on all aggregates to determine the profile of the particle size distribution of each aggregate and the results are shown in Fig. 1. Further parameters, such as dry-rodded density and fineness modulus, were ascertained in order to determine the characteristics of each natural and artificial aggregate, and the results of there are presented in Table 1. The particles of rubber are shown in Fig. 2.

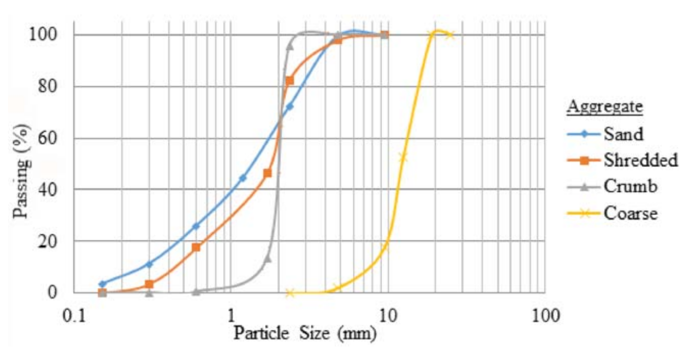

Fig. 1 Grain size distribution of natural and artificial aggregates

TABLE 1
FINENESS MODULUS AND DRY-RODDED DENSITY OF AGGREGATE

Aggregate	Fineness Modulus	Dry-rodded density (kg/m^3)
Crumb Rubber	3.90	587.46
Shredded Rubber	3.52	508.83
Sand	3.43	-
Coarse Aggregate	-	1504

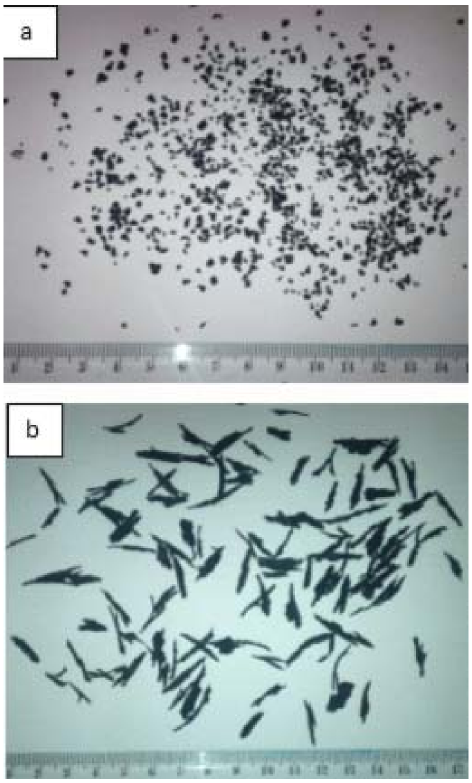

Fig. 2 Particles of a) crumb rubber and b) shredded rubber

B. *Production and Testing of Concrete*

Three different concrete mixes were produced, namely, the crumb rubber concrete (CRC), the shredded rubber concrete (SRC) and the reference concrete (RC). The concrete mixes were placed in a mechanical mixer for approximately 5 minutes in accordance with the mix proportion given in Table 2. Following the mixing, air content tests were conducted on the fresh concrete according to ASTM C231/C231M [4] to determine the percentage air in the mixture.

TABLE 2
CONCRETE MIX PROPORTION BY MASS (KG)

Material	Reference Concrete (RC)	Rubberised Concrete	
		Crumb Rubber (CRC)	Shredded Rubber (SRC)
Water	156	156	156
Cement	261	261	261
Sand	944	896.8	896.8
Coarse Aggregate (19 mm)	921	921	921
Rubber	0	21.81	21.81

Proceeding the mixing of concrete, several samples were made and vibrated for concrete testing. Three samples of 100-mm concrete cubes were cast for the compressive strength, absorption and porosity tests, respectively; three 100 × 100 × 500 mm rectangular concrete prisms were made for the ultrasonic pulse velocity test and flexural tensile strength test; and three samples of 100 × 50 mm diameter concrete cylinders for the impact test. Additionally, 71-mm concrete cubes were prepared for the abrasion test. The specimens used for the impact test were cured for 14 days, while the specimens for the other tests were cured for 28 days. Three specimens from each mix were used to determine the physical and mechanical properties of the concrete specimens.

Compressive tests were conducted on a Controls compressive tester in accordance with ASTM C39/C39M [5]. The compressive strength, f'_{cr}, was found using the formula, $f'_{cr} = \frac{P}{A}$, where P is the load at failure and A is the cross-sectional area.

The flexural tests were conducted using a Controls Pilot centre-point loading flexural test machine, according to ASTM C293/C293M [6]. The flexural tensile strength, R, was determined by using the formula $R = \frac{3PL}{2bd^2}$, where R is the modulus of rupture, P is the load at failure, L is the length of span, b is the average width of the specimen at fracture, and d is the average depth of specimen at the fracture.

To determine porosity, the saturated surface dried (SSD) mass was measured for each specimen after the 28-day cure, after which they were placed in an oven for 3 days at 40 °C and then weighed to obtain the dry mass. The porosity, P, in percentage, was then calculated using "(1)," where W_D is the dry mass and W_{SSD} is the SSD mass.

$$P = \frac{W_{SSD} - W_D}{W_D} \times 100 \quad (1)$$

The absorption test was conducted by first oven-drying the specimens to get a constant mass and then sealing the lower surfaces of the cubic specimens in order to ensure that the water was absorbed through the base only. The initial mass was then taken; then the specimens were placed on supports in water and immersed to a depth of 5 mm. Measurements were taken at 5, 15, 30, 60, 90 and 120 minutes following the immersion, and a graph was plotted to show the rate of absorption.

The abrasion test was carried out on a Bohme abrasion tester, according to the German standard DIN 52108 [7]. The initial specimen size was 71 × 71 × 71 ± 1.5 mm. The abrasion tester (Fig. 3) mainly consists of a 750-mm diameter steel disc rotating at 30 ± 1 cycles/min, a revolution counter, and a holding and loading device for the specimen. Abrasive dust (20 ± 0.5 g) was spread on the disc, and the specimen was attached. A load of 294 ± 3 N was applied to the specimen for 16 cycles in which 22 revolutions constituting one test cycle. After each test cycle, the specimen was cleaned and weighed. The grinding track was cleaned, strewed with new abrasive and the test specimen turned 90^o before clamped and loaded. The procedure was repeated for each specimen, and the wear losses were calculated after the 16 cycles. The abrasive dust used in this test was corundum (crystalline Al_2O_3).

Fig. 3 Abrasion test apparatus

The impact test was carried out, using a drop-weight mechanism, on 100 mm × 50 mm diameter cylindrical specimens after 14 days of curing. A 4.5-kg weight was placed 0.3 m above the centre of the specimen, and repeatedly dropped onto the surface. The number of blows for the first crack to visually appear and to cause total failure of the specimen was recorded.

III RESULTS AND DISCUSSION

A. Air Content

The air content test revealed that the rubberized concrete samples had higher air content than the ordinary concrete mix, as shown in Table 3. Ref. [8] conducted similar experiment and reasoned that it is possible for rubber to attract air, which would result in higher air contents of rubber samples. Further, the crumb rubber samples incorporated higher level of air than the shredded rubber sample which could be attributed to the fact that the grading of the crumb rubber was poorer than that of the shredded rubber.

TABLE 3
AIR CONTENT OF FRESH CONCRETE MIXES

Fresh Concrete	Air content, %
Reference Concrete (RC)	2.6
Crumb Rubber (CRC)	5
Shredded Rubber (SRC)	4

B. Porosity

Three 100 mm cubes that were saturated surface-dry were subsequently open dried to evaluate the porosity of the different types of concrete. The results of the porosity in the hardened specimens are given in Table 4. Statistically, within a confidence level of 95% ($\alpha = 0.05$) there are no differences in porosity among the specimens. However, it is seen that there is a greater loss in porosity in the shredded than with the crumb concrete when the sand was partially substituted with the rubber particles.

TABLE 4
PROPERTIES OF CONCRETE SPECIMENS, "±" ONE STANDARD DEVIATION OF THE SAMPLE

Con-crete	Poro-sity (%)	Compressive Strength (MPa)	Flexural Strength (MPa)	Impact		UPV, µs
				N_{crack}	N_{fail}	
RC	3.79 ±0.07	23.53 ±1.59	5.81 ±0.23	8	28	115
CRC	3.78 ±0.03	15.63 ±0.29	3.33 ±2.44	6	25	124
SRC	3.64 ±0.21	14.54 ±0.79	5.23 ±0.48	13	34	124

C. Ultrasonic Pulse Velocity

The results of the ultrasonic pulse velocity tests are given in Table 4. The results are the average from three 100 × 100 × 500 mm beams. The time for the ultrasonic wave to pass through the specimens was the shortest in the reference concrete while taking the longest time in crumb rubber concrete. The time was approximately shorter. This is an indicator that the non-rubberized samples possessed a higher density than the reference concrete.

Additionally, the UPV results show that the level of heterogeneity in the two types of rubberised concrete is approximately the same with the CRC just slightly more heterogeneous. This result is in alignment with the porosity and air content results which have indicated marginally greater heterogeneity in the CRC sample.

D. Absorption

Fig. 4 shows the graphs of the absorption tests for the specimens. All specimens displayed similar absorption capacity as the mass increased with time. By plotting the absorption (g/cm^2) as a function of the square root of time ($t^{0.5}$) a linear graph (Fig. 4) is obtained, and it shows that the ordinary concrete has the highest rate of absorption. Ref. [9] also studied the behaviour of cement-based pastes with the addition of very fine rubber particles when exposed to water. It was concluded that the rubberised paste showed a lower proclivity to the absorption of water. Obviously, higher volume of pores and the hydrophobic tendencies in the rubber samples account for this phenomenon.

Between the rubberised concrete samples, the degree of absorption is lower in the crumb rubber than the shredded rubber sample. Since the air content in the fresh CRC and the porosity of the hardened CRC sample are respectively higher than those of the SRC concrete, it can be concluded that either the sizes of pores are small, the connectivity between pores is low, or the transport path is tortuous relative to the CSC sample. Any of these attributes would suggest that the microstructure of the CSC is more refined than that of the RSC.

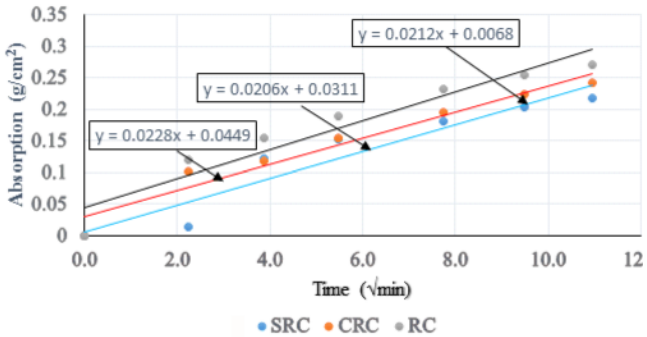

Fig. 4 Scatter diagram (markers) and best fit curve (lines) of the absorption of water in concrete specimens

E. Strength

The average compressive strengths for each type of concrete specimen are also shown in Table 4. Analysis of all these strengths shows that the strength of crumb and shredded rubber samples were approximately 34 and 38% less than the reference concrete. The reduction in compressive strength, according to Ref. [10], is ascribed to the weaker bond that is formed between the rubber and cement matrix. The lower bearing capacity, because of reduced stiffness, also contributed to the lower strength [11]. Comparing the rubber samples, it is observed that the crumb rubber sample achieved a higher compressive strength than the shredded rubber sample. The mechanics that is involved in the fracture of concrete samples under compression testing show that cracking is likely to develop in the weak interfacial transition zone (ITZ) between aggregate particles and matrix. The larger porous ITZ zones around the shredded particles would therefore account for the lower compressive strength in the SRC samples.

The results of the flexural tests are presented in Table 4. It is shown that the concrete experienced a reduction in strength when the rubber was incorporated in the concrete. This effect is similar to that shown in work done by other researchers [10] on traditional concrete with crumb rubber replacement. Calculated average reduction in strength is 10 and 43% for the SRC and CRC specimens, respectively, when compared to the RC. Again, the strength parameter of the rubberised concrete is decreased partly because of the reduced affinity for adhesion between cement paste and surfaces of the rubber particles. With regards to the rubberised concrete samples, the higher resistance to bending that is shown in the SRC samples may be the result of crack arrest in the vicinity of the multiple-prong elongated shredded particles.

In the comparison of the compression to flexural ratio, it is shown that, whereas the ratios for the RC and CRC samples are between 20 and 25, that of the SRC is greater than 35. The reduction in the tensile strength of rubberised concrete is significantly mitigated when the rubber is shredded.

F. Impact

Table 4 shows that the average number of blows for crack initiation (N_{crack}) and the number required for total failure (N_{fail}) of the concrete specimens. With reference to the RC sample, the CRC sample did not perform better in any of these two impact test parameters. For the size particles, the volume of the rubber used in the CRC sample may have been too low to have a pronounced effect on impact resistance.

On the other hand, the SRC specimens displayed higher resistance to crack initiation and post-cracking than the reference concrete. The higher resistance of the SRC specimen to impact forces is indicative of its high strain energy absorption capacity. The higher display of toughness is the usual trend as noted by Ref. [12] in a review on rubber incorporated concrete. Particle bridging was also observed at the cracks of the shredded rubber concrete, as shown in Fig. 5. Ref. [13] conducted a similar test and discovered that samples with shredded rubber had a higher post cracking strength than granular rubber as a result of particle bridging.

Fig. 5 Bridging of shredded rubber particles at crack

G. Abrasion

The graph in Fig. 6 shows that the ordinary concrete has the highest rate of mass loss from abrasion test. It was observed that after each cycle of abrasion, rubber particles emerged at the surface of the rubberized concrete. The existence of the rubber at the surface, through its toughness, offered high resistance to the abrasive action imposed on the samples and this phenomenon is attributed to the lower rate of mass loss in the concrete with artificial aggregates. The crumb rubber samples however, offered a better resistance to the abrasive force than the shredded rubber sample. The steady rate of attrition also suggests that the crumb rubber particles were more evenly distributed in the concrete than the shredded rubber particles. There is a very strong relationship between the total loss of material (y) and the compressive strength (x) of the concrete sample which is displayed in "(2)."

$$y = 0.3213x^2 - 12.11x + 116.57 \quad (2)$$

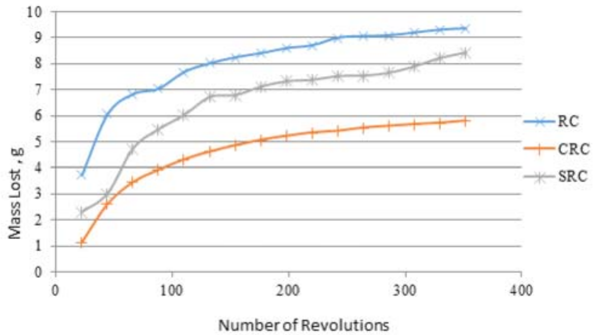

Fig. 6 Mass loss of concrete composites under nominal pressure of 58 kPa

IV CONCLUSION

In this study, the behaviour of concrete containing shredded and crumb rubber was investigated. The following are the main conclusions.

1. The research confirms that the flexural and compressive strengths of concrete are reduced when rubber particles partially replace fine aggregate.
2. The compressive strength of crumb rubber concrete is higher than that of shredded rubber concrete, but shredded rubber concrete has a higher flexural tensile strength than crumb rubber concrete. Additionally, the compression to flexural ratio is greatest in the shredded rubber concrete. This will be an important consideration when there is a need to mitigate the reduction in the tensile strength brought on by the use of rubberised concrete.
3. The addition of rubber increases the abrasion resistance of traditional concrete and fine crumb rubber is more effective in increasing the abrasion resistance. While the higher wear resistance in the rubber concrete samples is attributed to the higher toughness of the rubber particles, the effectiveness of the crumb rubber concrete in assuaging attrition is accredited to the higher uniformity in the distribution of the rubber particles in the matrix. A strong relationship between the total loss of material (y) and the compressive strength (x) of the concrete sample was established and this is shown in the equation: $y = 0.3213x^2 - 12.11x + 116.57$
4. The impact tests have shown that shredded rubber significantly improves concrete resistance to crack initiation and crack propagation. On the contrary, the crumb rubber did not improve the resistance of concrete to impact loads and it is postulated that, based on the particles size, higher volume of crumb rubber is needed to produce higher resistance to impact forces.
5. The absorption of water in concrete is reduced with the introduction of rubber particles.

ACKNOWLEDGMENT

The authors would like to gratefully acknowledge the contribution of Messrs N. Errar and B. Thomas to this research.

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