The Influence of Powdered Crumb Rubber on the Mechanical Properties and Thermal Performance of Lightweight Foamed Concrete

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Abstract. The introduction of powdered crumb rubber into the lightweight foamed concrete influenced various mechanical and physical behaviour of the concrete. The objective of this study is to investigate the influence of 15 %, 30 % and 45 % crumb rubber, in replacement of sand on the mechanical properties and thermal performance of lightweight foamed concrete. Compressive strength, flexural strength and thermal conductivity tests were conducted to evaluate the performance of crumb rubber lightweight foamed concrete. Laboratory results indicated that the strength properties of crumb rubber lightweight foamed concrete were weaker than those of conventional lightweight foamed concrete with a similar density. The compressive strength and flexural strength were reduced from 14.02 MPa to 10.66 MPa and 4.92 MPa to 3.06 MPa respectively, as the crumb rubber proportion was increased from 0 % to 45 %. However, it is worth mentioning that the optimum incorporation of 45 % crumb rubber in lightweight foamed concrete enhanced the thermal insulating performance by lowering the heat conductivity of the concrete from 1.1863 $W.K^{-1}m^{-}$ to 0.9733 $W.K^{-1}m^{-1}$.

1. Introduction

Increasing piles of waste tires have been one of the infamous environmental issues in modernized countries. According to Environmental Protection Agency (EPA), the accumulation of dumped tires at various landfill sites can pose severe health and safety hazards such as the habitation of rodent and mosquitos which will facilitate the spread of contagious diseases, increased risk of uncontrolled fires and production of toxic chemicals contaminating soil and vegetation. The amount of scrap tire generated has been skyrocketing as it is estimated to reach 1.2 billion tonnes annually by 2030 [1]. This is considered as one of the worldwide environmental challenges because waste tires are not biodegradable even after a long period of biological treatment. Burning of such wastes will induce serious air pollution involving the emission of poisonous gas to both human and environment. Thus, one of the effective solutions is the reuse of tire rubber as a partial replacement of aggregate in cement-based materials, known as rubberized concrete.

The aim of this study is to investigate the potential of crumb rubber to be adopted as one of the useful concrete components to enhance thermal properties of the concrete, and at the same time, minimize the existing environmental issue. In addition, another objective of this study is to examine the influence of crumb rubber on the mechanical properties and thermal performance of lightweight foamed concrete with the density of 1800 kg/m^3. The crumb rubber will be adopted to substitute fine aggregate in concrete at different proportions (15 %, 30 % and 45 %).

2. Experimental program

2.1. Mix proportion

The mix proportion of the control specimen (CR0) was set at 1.00:1.00:0.50 (cement: sand: water) and it contains no crumb rubber. The foam generated was introduced to the specimen until the fresh density of the fresh concrete dropped to 1800 kg/m^3. In the case of crumb rubber lightweight foamed concrete, powdered crumb rubber, as illustrated in figure 1, was utilized to replace fine aggregates at 15 % (CR15), 30 % (CR30) and 45 % (CR45) by volume fraction. The overall mix proportions of all specimen sets are summarized in table 1.

Figure 1. Crumb rubber particles with the maximum size of 40 mesh.

Table 1. The mix proportions of various specimen sets.

Designation	Weight per unit volume (kg/m^3)				
	Water	Cement	Sand	Crumb Rubber	Foam
CR0	357.45	714.90	714.90	0	12.83
CR15	370.85	741.70	630.45	45.47	11.62
CR30	385.25	770.50	539.35	94.46	10.31
CR45	400.9	801.80	440.99	147.44	8.92

2.2. Casting of the specimen

During the casting process, the concrete components including cement, sand and crumb rubber were dry-mixed in a ball mixer for 5 minutes. Water was then poured into the mixer for wet-mixing for another 5 minutes. After the concrete mix had attained homogenous condition, foam was introduced into the mix to lower the density of the fresh concrete to approximately 1800 kg/m^3. Eventually, the fresh concrete was cast and compacted into various moulds for subsequent laboratory tests.

2.3. Laboratory tests of the specimen

Three tests were conducted to accomplish the objectives of the study namely, compressive strength test, flexural strength test as well as steady-state heat flux measurement thermal transmission test.

As specified in the standard BS EN 12390-3, the concrete cube with dimension of 100 mm x 100 mm x 100 mm was fabricated as the compressive strength test specimen. The axial compressive load was applied on the specimen at the loading rate of 0.02 mm/s. The peak load attained prior to the ultimate failure of the specimen was taken as the compressive strength of the specimen.

In accordance with the requirements specified in the standard ASTM C496, the concrete rectangular specimens with the dimension of 160 mm x 40 mm x 40 mm were cast. The axial load of the flexural strength machine was pre-set to be 1.2 mm/min. The maximum load attained by each specimen was taken as the flexural strength of the specimen.

The thermal conductivity test was carried out based on the requirements stated in the ASTM C332 standard. The concrete cube specimens with the dimension of 50 mm x 50 mm x 50 mm were oven dried for 24 hours, and then cooled to room temperature prior to their placement in the steady-state heat flux machine. The cold plate with a temperature of 25 °C was placed at the top of the specimen while the hot plate with a temperature of 40 °C was placed at the bottom of the sample. The heat transfers and heat change between the two plates were recorded automatically by the data logger in every minute for one day. The specimens were covered by rubber insulators to minimize the effect of transfer of heat from the external surrounding.

3. Experimental results

3.1. Compressive strength test

Both table 2 illustrate the relationship between the compressive strength of concrete and the different crumb rubber proportions. It is clearly shown that the compressive strength drops as the crumb rubber ratio in the concrete increases. Both 7 days and 28 days' compressive strength of the concrete depicts a similar trend. One notable finding is that the 28 days' compressive strength of the lightweight foamed concrete only reduces slightly as 15 % of crumb rubber is used to replace the sand, which is from 14.02 MPa to 13.89 MPa (0.93 %). Beyond the crumb rubber proportion of 15 %, the compressive strength begins to decline vigorously. For instance, the 28 days' compressive strength of the lightweight foamed concrete descends to 10.66 MPa, upon the incorporation of 45 % of crumb rubber into the concrete. The reduction percentage is relatively significant and reported to be23.97 %.

It is found that the primary reason causing the decreasing of the compressive strength is the relatively low strength of the rubber particles [2]. As the crumb rubber proportion of the concrete increases in the concrete, the properties of the crumb rubber increasing tend to dominate the properties of the concrete resulting in the loss of strength. Besides, the decline in compressive strength of the concrete is generally due to the lack of adhesion between the cement paste and the smooth crumb rubber particles [3]. During the loading stage, cracks will emerge and develop quickly around the rubber particles which results in rapid rupture of concrete. In addition, the fine nature of crumb rubber also leads to the generation of voids in the hardened concrete. Benazzouk et al. [4] also reported similar behaviour as packing of crumb rubber particles becomes difficult at high substitution level due to the generation of voids. It was observed that reduction in the concrete compressive strength was also partially due to the lower stiffness of crumb rubber particles as compared to the original fine aggregate.

Table 2. The 7 days and 28 days compressive strengths of concrete cube specimens with different crumb rubber proportions.

Designation	7 days		28 days	
	Compressive strength (MPa)	Reduction percentage as opposed to the control sample (%)	Compressive strength (MPa)	Reduction percentage as opposed to the control sample (%)
CR0	13.00	-	14.02	-
CR15	13.29	-2.23	13.89	0.93
CR30	10.23	21.31	12.66	9.70
CR45	7.37	43.31	10.66	23.97

3.2. Flexural strength test

The relationship between the flexural strength of the concrete and the crumb rubber proportion is presented in table 3. Both 7 days and 28 days' flexural strengths of the concrete behave in the same manner as the crumb rubber ratio increases. However, the reduction in flexural strength is more obvious and drastic as compared to that in compressive strength. For example, the matured flexural strength (28 days) of the concrete descends from 4.92 MPa to 3.96 MPa, which is equivalent to 37.80 % of reduction, when 45 % of the fine aggregates are substituted by the crumb rubber.

The reduction in flexural strength is primarily due to inadequate bonding between the cement paste and the crumb rubber particles. Gupta et al. [5] claimed that the decrease in flexural strength relies on the size and shape of the crumb rubber. The smooth texture of the crumb rubber will accelerate the propagation of cracks during the loading phase and the overall resistance against the applied force will be reduced.

Table 3. The flexural strength of concrete rectangular specimen with different crumb rubber proportions.

Designation	7 days		28 days	
	Flexural strength (MPa)	Reduction percentage as opposed to the control sample (%)	Flexural strength (MPa)	Reduction percentage as opposed to the control sample (%)
CR0	4.85	-	4.92	-
CR15	4.69	3.30	4.37	11.18
CR30	3.88	20.00	3.82	22.36
CR45	3.03	37.53	3.06	37.80

3.3. Thermal conductivity test

Table 4 shows the variation in thermal conductivity of the concrete as the crumb rubber proportion increases. The final result was obtained by calculating the average value of thermal conductivity, which was generated and recorded once in an hour, and tested for 24 hours. A worth mentioning finding is that the thermal conductivity drops as the crumb rubber proportion in the concrete increases, and the decreasing trend is approximately linear with the change in crumb rubber proportion. The thermal conductivity of the concrete is decreased from 1.1863 $W.K^{-1}.m^{-1}$ to 0.9733 $W.K^{-1}.m^{-1}$, which is equivalent to 17.95 % of reduction.

The decline in thermal conductivity is most probably due to the insulating properties of crumb rubber particles in the concrete. Since crumb rubber essentially has a better insulating effect than sand, the employment of crumb rubber in replacement of sand simply implies that that insulating ability will be carried over to the resultant concrete as well. Another reason is that the rubber particles possess non-polar nature which tend to entrap air in their surface. Air entrapped in the porosity is not a good medium for the heat to be transferred.

Table 4. The thermal conductivities of concrete specimens with different crumb rubber proportions.

Designation	Thermal conductivity ($W.k^{-1}.m^{-1}$)	Reduction percentage as opposed to the control sample (%)
CR0	1.1863	0%
CR15	1.0737	9.49%

CR30	0.9969	15.97%
CR45	0.9733	17.95%

4. Conclusion

This paper examines the use of crumb rubber as a substitute of fine aggregate at different proportions through experimental study. Several conclusions can be drawn based on the findings obtained through a series of laboratory tests.

The incorporation of crumb rubber in the lightweight foamed concrete will induce reduction in the strength properties of concrete, both compressive strength and flexural strength. However, the reduction in compressive strength is almost negligible (0.93 %) if the substitution of sand by crumb rubber does not exceed 15 %. For higher crumb rubber proportion, the compressive strength declines at a greater rate. The reduction in compressive strength when 45 % crumb rubber is introduced to the lightweight foamed concrete is reported as 23.97 %. In term of flexural strength of the concrete, a strong reduction effect by crumb rubber proportion can be spotted. At 45 % crumb rubber proportion, the flexural strength is reduced by 37.80 % as compared to the one without crumb rubber.

However, crumb rubber lightweight foamed concrete exhibits superior thermal properties than plain lightweight foamed concrete. This is proved by the decrease in thermal conductivity, from 1.1863 $W.K^{-1}.m^{-1}$ to 0.9733 $W.K^{-1}.m^{-1}$ (17.95 %) as 45 % of crumb rubber is introduced to the plain lightweight foamed concrete.

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