Fresh and Hardened Properties of Innovative Foamed-Rubberized Concrete

Essam Eltayeb, Xing Ma, Yan Zhuge and Osama Youssf

Abstract Foamed concrete has many superior properties including lightweight, high thermal and acoustic insulations. Crumb rubberized concrete also attracts interests from researchers throughout the world because of its ductile performance especially under dynamic loads and its environmental benefit to reduce the pollution impact from end-of-life tires through recycling rubber particles in concrete. It is expected that foamed-rubberized concrete has the combined advantages of both foamed concrete and crumb rubberized concrete. In this paper, fresh and hardened properties of this cellular concrete are investigated including, density, flowability, compressive strength, splitting tensile strength, flexural strength, Young's modulus of elasticity and poison's ratio. Foam cells in concrete are produced through using chemical foaming agent and foam generator. Crumb rubber particles with about 4.75 mm maximum sizes were added to the concrete matrix as sand replacement by volume with varying ratios, 0, 10, 20 and 30%. The cement content and water/cement ratio are fixed at 550 kg/m^3 and 0.5, respectively and the sand/cement ratio is equal to 1.5. Cylinder and beam specimens were tested and the experimental results are presented, plotted and tabulated for comparison.

Keywords Foamed concrete · Crumb rubber · Cellular concrete · Mechanical properties

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1 Introduction

Foamed concrete (FC) is defined as a cellular concrete that can be classified as a lightweight concrete of density range from 400 to 1850 kg/m^3 with random air-voids created by mixing foam with the base mixture [3]. Compared with normal concrete (NC), foamed concrete has many advantages such as high flowability, low density, minimal consumption of aggregate [14], high strength to weight ratio, excellent thermal insulation properties [3, 14, 15], high fire resistance and good sound insulation properties [2]. However, foamed concrete has lower strength, and modulus of elasticity than normal concrete. Like all other types of concrete, foamed concrete consists of basic and supplementary components. The basic components for the foamed concrete are cement, sand, water and foaming agent, whilst the supplementary materials are fly ash, silica fume super-plasticizers, and fibers [3]. The properties of foamed concrete are affected by the mixture components, percentages and the method of mixing. The effect of the different factors on the properties of foamed concrete have been studied by researchers such as cement types and cement contents, (C), water/cement ratios, (W/C), sand grades, sand/cement ratios, (S/C), foaming agent types and contents, fly ash as a binder material and its contents, silica fume contents, steel fibers percentage, artificial fiber types and contents and superplasticizer or water reducer types and contents.

On the other hand, rubberized concrete (RC) is a type of sustainable construction material that contains rubber particles from used tires as a partial or a full replacement for coarse (stone) or fine (sand) aggregate or both. Rubberized concrete has been studied and investigated by researchers since 1991. It is one of the most interesting topics in construction field because of two reasons. The first reason is related to the environmental impact from the huge number of tires that reached their end of life every year. The second reason is related to the limited resource of the natural aggregate (sand and stones). Many researches have been carried out to study RC including its mechanical properties, dynamic properties, durability, electric resistance, heat transfer and thermal resistance, fire resistance, sound resistance density and workability properties. Experimental studies on RC materials have shown that using rubber in concrete as a partial replacement of mineral aggregates enhances its ductility, toughness, impact resistance, energy dissipation, and damping ratio [1, 8]. However, it reduces its compressive strength, tensile strength, and modulus of elasticity compared with conventional concrete [7, 16–18].

While there has been a wealth of research investigating the properties of recycled rubber tyres incorporated in conventional concrete, few researches have been conducted to study the properties of foamed concrete containing rubber particles from used tires. Foamed-rubberized concrete (FRC) benefits from both advantages of foamed concrete (lightweight, self-compacting, thermal and acoustic insulation and fire resistance) and rubberized concrete (high energy dissipation, high damping, high ductility, toughness and impact resistance). The main problem for developed this hybrid concrete is the low compressive, tensile, flexural strength and modulus of elasticity. Due to its low strength, this concrete material was only used as filler material. Kadir et al. [10] conducted a research on lightweight foamed concrete containing cement, sand, water and foam. Rubber powder waste (RPW) with a percentage of 0, 3, 6 and 9% of cement weight was added to the mixture. The results showed an unexpected increase in compressive strength with the increase in RPW. The compressive strength at 28 days was 12.7, 22.3, 27.9 and 28.3 MPa with the inclusion of RPW of 0, 3, 6 and 9% respectively. Kashani et al. [12] conducted a research on lightweight foamed-crumb rubberized mortar without sand. The weight of rubber used was 0, 10, 20 and 30% of total solid mass. The research concluded that the tested specimens showed an excellent sound and thermal insulation with very low water absorption and total porosity by inclusion of recycled tyre crumb in lightweight foamed concrete. The results showed around 10% reduction in compressive strength by adding 10% of rubber. An increasing rubber content to 30% reduced the compressive strength by 50% compared with the control specimen. The compressive strength at 7 days reduced from 1.6 MPa at 0% of rubber to 0.8 MPa at 30% rubber without pretreatment. Hilal [9] partially replaced sand by crumb rubber with 0, 20 and 30% volume percentages in foamed concrete. The compressive strength was 17.21, 13.62 and 10.71 MPa for foamed concrete containing 0, 20 and 30% rubber. They also reported a reduction in tensile and flexure strength for the rubberized concrete specimens. The impact resistance increased with the increase of rubber content. Kashani et al. [11] studied the effect of using five different rubber pretreatment methods on the compressive strength and workability of foamed mortar. They concluded that the silica fume coating is the most feasible methods for improving the compressive strength of foam mortar with recycled crumb rubber.

To that end and to the best of the authors' knowledge, there are very limited researches that studied the use of crumb rubber as fine aggregate replacement in foamed concrete. This research provides experimental investigations on the fresh and hardened properties of foamed-rubberized concrete (FRC) to help better understanding of this material.

2 Experimental Program

2.1 Materials

General purpose Portland cement according to the Australian Standards, AS 3972 [4], was used as the binder material in the concrete mixtures. The crumb rubber used in this research had particle sizes of 2.36–4.75 mm and was used as a partial replacement of sand by volume. The sieve analyses for the used sand and crumb rubber are shown in Fig. 1. The specific gravity, fineness modulus, and unit weight were 2.61, 2.20, and 1420 kg/m^3, respectively for sand and 0.97, 4.85, and 530 kg/m^3, respectively for crumb rubber. A Sika SB2 liquid surfactant (a commercial, synthetic based foaming agent) with a specific gravity of about 1.04 was used in this study by diluting in water with ratio 1:50 by weight and charged in a foam generator machine

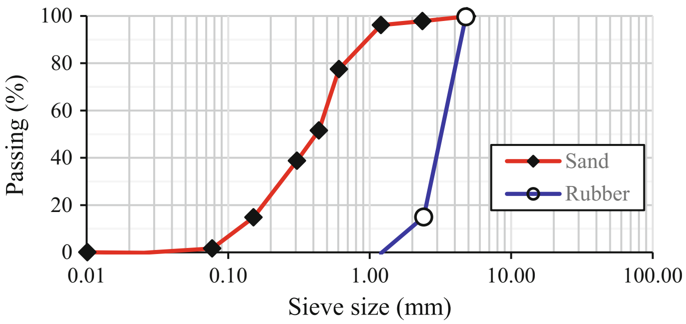


Fig. 1 Sieve analysis of the used aggregates

to produce a preformed stable foam wit density of about 41 kg/m^3 (stable foam density range from 40 to 70 kg/m^3 as recommended by ASTM C 796-97 [6]) to be mixed with the base mixture and produce foamed concrete.

2.2 Concrete Mix Design

In general, there are no specific mix proportion methods to obtain the target properties of the foamed concrete as there are many factors that affect the FC properties such as concrete density, cement content, W/C ratio, S/C ratio and foam volume. However, some trial and error methods are utilized to design the appropriate mix [3]. Several trail mixes have been carried out to produce foamed concrete using cement content ranging from 400 to 550 kg/m^3, W/C ratio ranging from .40 to .60 and S/C ratio of 1, 1.5 and 2. The most important and difficult thing for the foamed concrete mix design is to achieve the target fresh density with a good workability and consistency where the actual density and the design density are closed to each others with a maximum difference of about ±50 kg/m^3 as recommended from the literature and accepted in the industrial sector [14]. The target design density of FC used in this research is 1650 kg/m^3 which is selected from different trial mixes to give a minimum 28 days cylinder compressive strength of about 15 MPa. Total water-cement ratio (including the water used to produce foam using the foam generator) is equal to 0.5 for all mixes to achieve the required flowability without any water reducing agents and it was found to be suitable to achieve a good consistency. Sand/cement ratio is equal to 1.5 and the cement content is equal to 550 kg/m^3. Foam volume is equal to 24.4% of the total mix's volume. The foaming agent was diluted in water by 1:50 by volume and compressed under 60 psi pressure using air compressor connected to the foam generator. The measured foam density was 41 kg/m^3. Crumb rubber was used to replace sand by 10, 20 and 30% by volume. As a result, five mixes were prepared. The first mix was cement-sand mortar used as a reference (without any foam or rubber). The second mix was lightweight FC without any rubber and the other three

Table 1 Mixes proportions

Mix code	R (%)	Mix proportions (kg/m^3)						Design density (kg/m^3)
		Cement	Sand	Water	Rubber	Foam	W/TS	
MR	0	718	1077	359	0	0	0.2	2155
FC	0	550	825	265	0	9.9	0.2	1650
FRC-10	10	550	742.5	265	30.7	9.9	0.208	1598
FRC-20	20	550	660	265	61.3	9.9	0.216	1546
FRC-30	30	550	577.5	265	92	9.9	0.226	1495

Where: *W* water, *TS* total solid materials (cement + sand + rubber), *R* rubber content

mixes were foamed-rubberized concrete (FRC) with 10, 20 and 30% rubber-sand replacement by volume. Table 1 shows the mixes' proportions.

2.3 Concrete Mixing and Specimens' Preparation

The mixing procedure for all mixes was as follows: mix dry sand, rubber (if any) and half of the water for 30 s in a pan mixer; rest for 1 min; add cement and the remaining water and then mix for 2 min; rest for 2 min; add the required amount of foam (if any) and then mix for 2 min or until the foam is completely mixed with the mortar (if any) which took from 2 to 3 min. For the foamed concrete mixes, the fresh densities were measured by filling a container with a known volume and measuring its weight (empty and full weight). When the measured fresh density of the foamed concrete was close to the design density (±50 kg/m^3) then the mix was accepted, otherwise if it was higher, more foam was added to the mixture to achieve the required density with the accepted tolerance. The Australian standard slump was filled with the foamed mortar without any compaction to avoid any damage to the air bubbles and then left over to let it flow over the base plate and measure the slump diameter as a measure of the workability for the mixture as shown in Fig. 2. Cylinders with 100 × 200 mm dimensions (3 cylinders for 7 days compressive strength, 3 cylinders for 28 days compressive strength, 2 cylinders for 28 days splitting tensile strength and 2 cylinders for modulus of elasticity and the poison's ratio) and three beams with 100 × 100 × 470 mm dimensions (for the 28 days flexural strength tests) for each batch were then filled with the mixture without compaction and the specimens were only gently tapped using a rubber hummer to get its outer surface smooth as recommended by ASTM C 796-97 [6]. The specimens then left to dry in a room temperature of 18 °C at the UniSA structural lab for 24 h and then the specimens were demolded and curried in a cabinet with a temperature and humidity control (around 24 °C and 95%, respectively) to the date of testing. Table 2 shows the values of the densities and the fresh properties of the different mixes.

Fig. 2 Slump flow measuring

Table 2 Fresh properties of the tested specimens

Mix code	Design density (kg/m^3)	Actual wet density (kg/m^3)	Average dry density (kg/m^3)	Consistency = (3)/(2)	Average slump diameter (mm)
(1)	(2)	(3)	(4)	(5)	(6)
MR	2155	2168	2154	1.006	705
FC	1650	1661	1617	1.007	635
FRC-10	1598	1593	1555	0.997	603
FRC-20	1546	1510	1463	0.976	605
FRC-30	1495	1519	1471	1.016	600

2.4 *Tests and Mechanical Properties*

Different tests were performed to understand the behavior of foamed-rubberized concrete (FRC) compared with its equivalent foamed concrete (FC without rubber) and the base mortar (MR without foam or rubber). Six cylinders for each batch were tested for compressive strength at the ages of 7 days and 28 days using the AutoCon compression machine at the structural lab at UniSA. The loading rate was chosen as 1.2 kN/s according to American standards ASTM C39 [5]. The values of the compressive strengths and failure modes are given in Figs. 3 and 8. In addition, two cylinders at the age of 28 days from each batch were tested for the splitting tensile strength as shown in Fig. 4 and 5. The loading rate was 0.8 kN/s and the results are given in Fig. 8. Three beams with dimensions of 100 × 100 × 470 mm at the age of

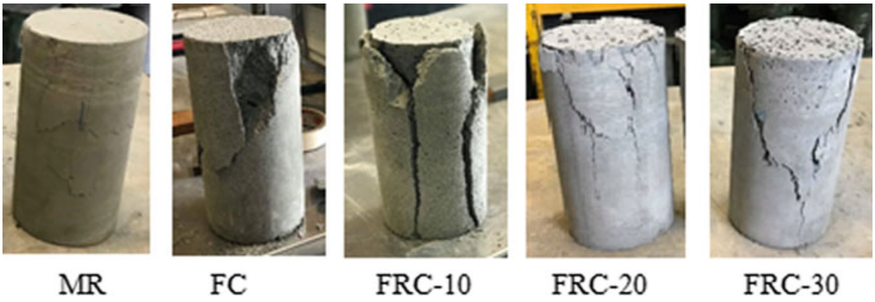
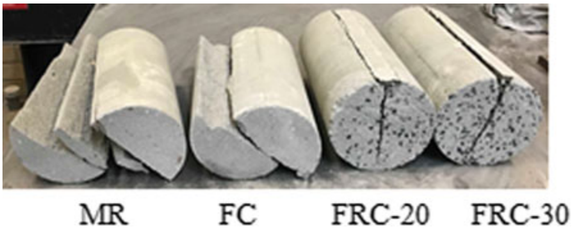


Fig. 3 Failure modes of the tested specimens under compression

Fig. 4 Splitting tensile strength test procedures

Fig. 5 Failure shapes for the tested specimens under splitting tensile loads



28 days of each batch were tested for flexural tensile strength. Four-points flexural loading tests with a loading rate of 0.017 MPa/s were conducted as shown in Fig. 6.

Two cylinders each batch were tested under the Baldwin machine (as shown in Fig. 7) to measure the modulus of elasticity (E_c), poison's ratio (ν) and the stress-strain behavior of the different types of concrete, where four strain gauges with two in horizontal direction and two in vertical direction were fixed on the specimen surface. The displacement control loading method was employed with the loading rate of 0.001 mm/s. The modulus of elasticity and the poison's ratio were calculated according to the Australian Standards and presented in Fig. 8.

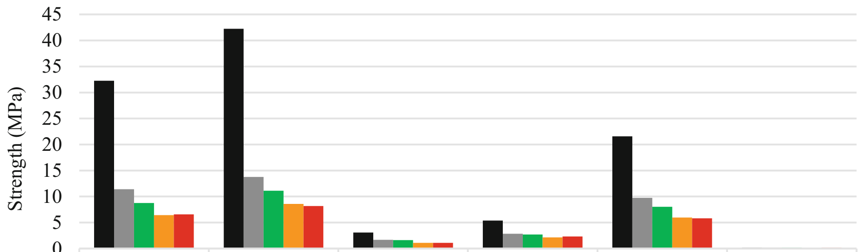
Fig. 6 Flexure test set-up

Fig. 7 Modulus of elasticity test set-up

3 Results and Discussion

3.1 Fresh Properties

Densities of mixes were measured in two phases; fresh and air-dry. Fresh density is usually used to calculate the actual volume for the design mix while the dry density controls the mechanical properties of foamed concrete [3]. The measured fresh density of all foamed concrete mixes were within the required consistency and stability requirements with about ±50 kg/m^3 as recommended from the literature [3]. The results showed that adding preformed foam with about 24.4% of total mix volume reduced the total consumption of cement and sand weight as well as fresh density by 23.4%. The fresh density of the foamed concrete reduced by 4.1, 9.1 and



	7 days Comp. Mpa	28 days Comp. Mpa	28 days Splitt. Mpa	28 days Flex. Mpa	28 days Ec. GPa	28 days vc.
MR	32.25	42.24	3.08	5.369	21.58	0.184
FC	11.41	13.76	1.69	2.839	9.75	0.163
FRC-10	8.75	11.12	1.62	2.714	8.02	0.156
FRC-20	6.44	8.59	1.11	2.136	5.97	0.108
FRC-30	6.59	8.18	1.1	2.319	5.83	0.176

Fig. 8 Results of the tested specimens

8.5% with 10, 20 and 30% inclusion of CR, respectively. The density of the FRC-20 batch was less than the density FRC-30. The possible reason might be the additional amount of foam that was added during the mixing in order to achieve the acceptable target density. The foam volume in this mix was higher than in FRC-30 and that is why the two mixes' densities become close to each others. The same trend was observed for the air dry densities for all mixes which were carefully measured for all cylinders at the testing day. The difference between dry densities and fresh densities for all mixes achieved the acceptable tolerance with about ± 50 kg/m^3 as mentioned by Amran et al. [3].

The average slump diameter for the foamed concrete mixes were insignificantly reduced from 635 mm for the FC mix to 600 mm for FRC-30 with the inclusion of 30% CR. The slump reduction phenomenon was also observed in rubberized concrete. One potential reason might be: the reduced concrete self-weight which reduced its ability of free flowing. The second reason might be the effect of inter-particle friction that occurs between the rubber particles and the other mix constituents [13].

3.2 *Hardened Properties*

The results of the 7 days compression tests showed a significant reduction of 64.6% for the foamed concrete mix compared with the control mix without foam and about 67.4% reduction for the 28 days compressive strength. The results also showed an additional reduction of about 23.3, 43.6 and 42.2% in the 7 days compressive strength for the mixes with 10, 20 and 30% CR, respectively compared to the foamed concrete mix. The same trend was observed for the 28 days compressive strength. However, this reduction rates slightly reduced to 19.2, 37.6 and 40.6%, respectively. This behavior indicated an improvement of the FRC mixes strength with time. A sudden failure with booming sound was observed for the control mix (MR). A brittle failure with a combined conical and splitting failure was observed for the foamed concrete mix. However, the foamed rubberized concrete specimens showed a ductile failure with relatively wider cracks as shown in Fig. 3.

The 28 days tensile strength for the FC mix reduced by 45.1% compared with the control mix (MR) which is significantly less than the reduction rate for the 28 days compressive strength. A slight reduction of about 3.5% for the 28 days tensile strength was observed for FRC with 30% crumb rubber, which is much smaller than the 40.6% reduction in the 28 days compressive strength. This is because the rubber particles works as ductile springs that delay the cracks and increase the concrete ability to sustain tensile forces across the cracks. The same behavior was observed for the rubberized concrete research in the literature. In addition, the flexure strength of the foamed concrete mix was reduced by 47.1% compared with the MR mix without foam and 4.4, 24.8 and 18.3% for the foam concrete mixes with 10, 20 and 30% rubber compared with the foamed concrete mix without rubber. A ductile behavior was observed for the FRC specimens under tensile and flexural loads as shown in Fig. 5.

The modulus of elasticity and poison's ratio were calculated according to the Australian standards (unfortunately only two cylinders for each mix were tested instead of three cylinders due to some lab limitations) the results shown in Fig. 8 are the average values of the tested cylinders for each mix. The results showed a significant reduction rate of 54.8 and 11.41% in the modulus of elasticity and poison's ratio for the FC mix compared with the MR mix. This is because of 25% reduction in the concrete weight. The inclusion of 10, 20 and 30% of rubber in foamed concrete leaded to a reduction of about 17.7, 38.8, 40.2% in the concrete modulus of elasticity and 4.3, 33.74 and 8% in poison's ratios and, respectively. The results of the poison's ratio for the FRC-30 mixes does not follow the same trend. Figure 9 shows the effect of rubber content on the several properties of foamed concrete (the results of FRC-20 mix is excluded from this diagram because its behavior is affected by the increase in foam instead of the rubber content).

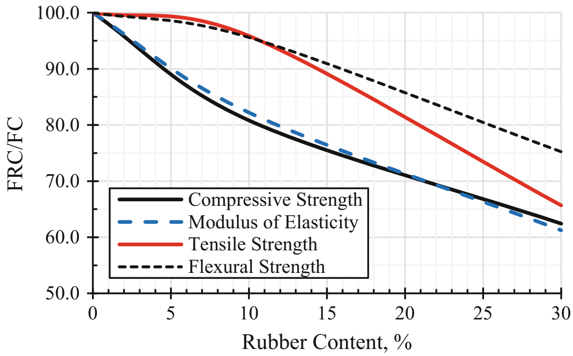


Fig. 9 Properties of foamed rubberized concrete related to foamed concrete

Comparing the results of FRC-20 and FRC-30 mixes, the behavior of both mixes is almost the same regardless the different rubber percentage. It can be concluded that the main properties are only affected by the mixture density.

4 Conclusions

In conclusion, acceptable target density for FC and FRCs could be achieved using the method provided in this paper. The addition of rubber particles slightly reduced density and flowability of foamed concrete. Compressive strength and modulus of elasticity reduced significantly in FRC compared with FC. However, the reductions in split tensile strength or flexural tensile strength was much more mild. The above properties did not change much for FRCs with 20% crumb rubber and 30% crumb rubber but with the same density. Finally, foamed rubberized concrete specimens exhibited a ductile failure and large deformations compared to the foamed concrete without rubber.

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