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MECHANICAL PROPERTIES OF A DEVELOPED FOAMED CONCRETE

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ABSTRACT

This paper investigates the mechanical properties at a fresh and hardened states of a new foamed concrete. The aim is to develop and produce a hydrophobic lightweight foamed concrete with enhanced properties for structural use. Foamed concrete generally is made of ordinary Portland cement (OPC), fine aggregates, foaming agent, admixtures and water. Metakaolin (MK) and water reducing admixture were used with the mix in this study. The physical properties of the mixes in their fresh state, mainly the consistency of the mixes was determined. All the mixes prepared were undergone rheology test at fixed water/cement (w/c) ratio of 50%, testing for flowability and spreadability. Compressive strength testing was carried out on 100 mm cubes and the results revealed that the compressive strength of foamed concrete decreases with a reduction in density. Flexural strength and flexural modulus, which were tested on 100 x 100 x 500 mm prisms, were also found to decrease with the reduction in density. The use of MK improved compressive strength as well as flexural strength development for normal and foamed concrete. Higher improvement was noted for the flexural strength with the use of a higher dosage of MK.

***KEYWORDS*:-** Compressive strength, Flexural modulus, Flexural strength, Foamed concrete, Metakaolin and Water reducing admixture.

I. INTRODUCTION

FOAMED concrete (FC) is a composite material, generally consists of ordinary Portland cement (OPC), fine aggregate (sand), foaming agent (which is an air entraining agent), admixtures and water, (Ramamurthy et al. 2009; Panesar 2013). For the last two decades, it has been used as a filler for trenches and gap filling owing to its main characteristics of being self-flowing and self-compacting with good flawability. At present, it is generally used in building construction as low strength concrete for foundations, thermal and sound insulations, and in areas where resistance to frost is a requirement. It is also used for making thin sections such as partition insulating thin walls, thin slabs, building blocks and bricks. Foamed concrete can be produced to have densities between about (400 and 1800) kg/m^3 (Mydin and Wang 2011), and have different properties with different compressive strengths of (1-15) N/mm^2, while 25 N/mm^2 is set as the minimum strength for structural uses (Jones and McCarthy 2005). The density of concrete varies as does its compressive strength depending on the type of aggregates used in the mix, but is around 2,400 kg/m^3 for normal weight concrete and between (400 – 1850) kg/m^3 for FC (Amran et al 2015). Void sizes can vary depending on the type of material used to produce the foam or air trapped bubbles. According to (Mydin and Wang 2011) and (Kearsley 1999) cellular concrete contains voids with a diameter of between (0.1 and 1) mm. However, (Brady et al. 2001) stated that the bubbles in foamed concrete vary in size from around (0.1 to 1.5) mm in diameter. (Mydin and Wang 2011) also stated that the bubbles are distributed uniformly in either a matrix of aggregate and cement paste or in the cement paste alone.

There are a number of supplementary materials which are used to improve the mechanical and physical properties of FC, for instance, Silica Fume is used to enhance the strength of FC in a short time due to their filler characteristics and pozzolanic behavior (Jones and McCarthy 2005; Nambiar and Ramamurthy 2006). Whereas, fly ash requires a longer time to reach the maximum strength compared to cement (Kearsley and Wainwright 2001). Therefore, the complementary by-products should be used as partial replacements according to desirable properties of FC.

Metakaolin (MK) is a “pozzolanic” additive product used as a supplementary cementitious material in concrete. Works in this field show that MK inclusion has a good influence on durability, as well as the physical and mechanical properties of concrete (Ding and Li, 2002; Brooks and Johari, 2001; Gleize et al. 2007; Khatib and Clay, 2004). Concrete, which contains Mk, exhibits favourable engineering properties. (Nambiar and Ramamurthy, 2006) stating that the use of MK improved compressive strength development at all test ages. This is due to the characteristics of MK, leading to an improved aggregate-matrix bond associated with the formation of a less porous interfacial zone. The “pozzolanic” reaction starts soon after the addition of water and continues up to between 7 to 28 days. Mk is made from heating up kaolin-containing clay. MK typically contains 50–55% SiO_2 and 40–45% Al_2O_3 (Poon et al. 2001). Other oxides present in small amounts include Fe2O3, TiO2, CaO and MgO. Even though there are a number of researchers (Amran et al. 2015; Panesar 2013; Jones and McCarthy 2005) considering the FC as their main field of work, however, they took a little interest in Metakaolin inclusion within their field of research. Hence, for this experimental work, water reducing admixture was used with some mixes contained MK, particularly at 50%, which is highly reactive with the cement and has a high demand for water absorption.

Foaming agents are commonly protein-based, synthetic, glue resins, detergents, hydrolyzed protein, resin soap, and saponin (Bing et al. 2012; Van Dijk 1991). Foaming agents are classified based on the active ingredient. The most common foaming agents are protein based, synthetic based and enzyme based. The protein based foam agents result in a stronger and a more closed-cell bubble structure, which permits the inclusion of greater amounts of air and provides a more stable air void network while the synthetic ones yield greater expansion and thus lower density (Amran et al. 2015). The content of the foaming agent has a considerable effect on the properties of fresh and hardened concrete. Therefore, the mechanical and physical properties of FC can vary depending on the type of foaming agent and dosage used in the mix (Panesar 2013). It has been reported that the excessive foam volume results in a drop in flow, decrease in density, and decrease in compressive and tensile strengths (Amran et al. 2015). Standard protein based foaming agents are formed by the process of protein hydrolysis using animal proteins from horn, blood, bones of cows or other remainders of animal carcasses. While Synthetic foaming agents are amphiprotic substance that are strongly hydrophilic and easily dissolve in water yielding air bubbles. However, when introducing synthetic agents into concrete, which is a complex chemical environment, the compatibility of surfactant and cement particles is critical to effectively entrain the desired air content and concrete microstructure (Panesar 2013).

There are two techniques that could be used in the process of producing FC which are pre-foaming method and mix-foaming method, (Karl and Wörner 1994). The pre-foaming method involves producing the base mix and the foam separately. Then, the foam is completely blended into the concrete paste. The foam could be produced by either dry or wet method. The dry foam is generated by pushing the diluted foaming agent using a pressurised vessel. It is reported that the foam is stable with small size bubbles generally less than 1mm (Amran et al. 2015). The wet foam is produced by spraying the foaming agent solution through a fine mesh. The wet foam bubble size is generally between 2 and 5 mm, and is considered to be less stable compared to the dry foam (Pugh, 1996). In the mixed foaming method, the surface active agent is mixed along with base-mix constituents specifically with cement slurry during the mixing process. The obtained foam results in a cellular structure in the foamed concrete. The foam should be steady and stable to be able to resist the mortar pressure until the cement initially sets. This helps to build up a strong skeleton of concrete all over the voids filled with air (Amran et al. 2015).

As review of the literature reveals, behavior of MK and the combination of MK with water reducing admixture have not been examined with foamed concrete (FC) at different densities before. Therefore, this paper examines the use of MK at 20% and 50% partial replacement of OPC for different densities, with and without the aid of water reducing admixture where applicable for the advancement of FC. The mechanical properties investigated for this purpose are, rheology at the fresh state, and strength and permeability at the hardened state for foamed concrete.

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II. EXPERIMENTAL WORK

The experiments were carried out in the laboratory in accordance to the relevant British Standards (BS) for each part of the process. Sets of 100 x100 x 100 mm cubes, and 100 x 100 x 500 mm rectangular prisms were prepared from 10 batches of different concrete mixes, made with OPC and sand. Plastic moulds were used to cast the normal weight concrete samples. Whereas, disposable polystyrene cube moulds were used to cast all concrete samples containing foam. This is to avoid the use of (a) release agent and (b) delay the demoulding process up until the end of the curing period of 28 days. The process began by sieve analysis to determine the particle size distribution for natural sand in accordance to BS 11277:2009. The sand was dried out prior to the test at 105 ^{o}C, and then cooled down to 20 ^{o}C ± 2 at room temperature. Suitable scales were used to weigh the ingredients. An electric concrete mixer was used in accordance to BS 1881-125:2013 to mix all the dry ingredients together thoroughly prior to adding the water.

The foam was added at different percentages to the mixes to produce the desired densities. The foaming agent used in this project was a protein based foaming agent. Dry pre-foaming method was used to generate the foam as shown in Fig. (1). The mix design composition of all the batches and their designation are presented in Table (1).

Fig. (1): The device used to generate the foam

Concrete specimens with normal densities but without foam were cast, to be used as controlling figures for comparison purposes.

The main tests carried out were plastic density and rheology of the fresh state (flow and spreadability tests), compressive and flexural strength in the hardened state, (using crushing machine), permeability (using permeability testing device), and freeze and thaw (through environmental chamber), see Figs. (1, 2a -2c and 3 - 6).

Fig. (2a): Spread test

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TABLE (I): Mix Design Compositions and Their Designatio

	Type of concrete cast:	Mix ratio	Dry density kg/m³	OPC %	MK %	Sand %	Admixture %	Spreadability mm	Specimen labelling subjected to Freeze & Thaw test
S1	OPC and Sand	1:1	2000	100	0	100	-	**640**	**SF1**
S2	OPC and Sand	1:2	2100	100	0	200	-	**610**	**SF2**
S3	OPC 80%, MK 20%, and Sand	1:2	2100	80	20	200	-	**580**	**SF3**
S4	OPC 80%, MK 20%, Sand and Foam (at different %)	1:2	1650	80	20	200	-	**560**	**SF4**
S5	OPC, Sand and Foam	1:2	1200	100	0	200	-	**670**	**SF5**
S6	OPC 80%, MK 20%, Sand and Foam	1:2	1900	80	20	200	-	**600**	**SF6**
S7	OPC 80%, MK 20%, Sand and Foam	1:1	1650	80	20	100	1	**710**	**SF7**
S8	OPC 80%, MK 20%, Sand and Foam	1:2	1800	80	20	200	1	**740**	**SF8**
S9	OPC 50%, MK 50%, and Sand	1:1	1500	50	50	100	1	**880**	**SF9**
S10	OPC 50%, MK 50%, Sand and Foam	1:1	1300	50	50	100	1	**850**	**SF10**

Fig. (2b): Flow cone

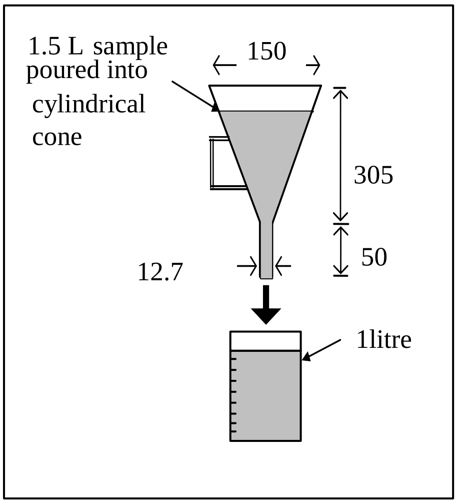

Fig. (2c): Dimensions of flow cone (mm)

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Fig. (3): Permeability testing device

Fig. (4): Freeze and thaw chamber

Fig. (5): Automated computerised compressive test

Fig. (6): Prism under 4-point load test

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III. RESULTS AND DISCUSSIONS

Rheology Test

All the mixes prepared underwent rheology test at a fixed w/c ratio of 50%, testing for flowability. Closely related to this is the bubble stability and stability period of the foam used in the concrete mixture. The bubbles produced expected to hold still for about 30 min during which concrete is well placed before bubbles dying out. One way to test for rheology is to test for consistency. The consistency of both the base mix and foamed concrete is to be measured by spreadability. The spreadability variation with mix density before and after addition of foam is measured through using slump cone (Brady et al, 2001), see Figs. (2a – 2c).

Results show, spreadability was increased for the specimens (S7 – S10) which were of low densities and contained water reducing admixture. The reason for this may be due to the presence of the water reducing admixture, causing the bubbles of the foam to collapse, decreasing the stability of the foam and produce a more diluted mix, while early hydration rate of the mix is unpredictable when high doses of MK are present, as a result, spreadability is increased. While spreadability was reduced when the foam was added for the other low density specimens, namely (S2 – S5), see Fig. (7). (Nambiar and Ramamurthy 2006; Nambiar and Ramamurthy 2008) suggested that the reason for this behavior may be due to the adhesion between the bubbles and the solid particles in the mixture, which increases the stability of the paste, resulting in reduced spreadability. Noting that there were more bubbles at the low densities. MK absorbed more water initially, that is why higher doses of MK, needed some form of water compensation. This comes from either the water reducing admixture (if available), or otherwise from the foaming agent, causing the bubble structure to break and collapse, resulting in a rather denser mix. It was also noted that MK was highly reactive with the cement, evolving high heat of hydration. As a result, some initial thermal cracks were apparent, particularly with the prisms made with MK at 50% for which its weakness may come from. The water reducing admixture proved to have no compatibility with the foaming agent. It was noted that bubbles of the foaming agent died out much quicker than usual because of their reaction with the admixture.

Compressive Strength Test

Specimens were casted and cured, then examined for compressive strength and flexural strength tests at the age of 28 days by controlled crushing in the lab. In addition, flexural modulus was worked out. Compressive strength testing was carried out on 100 x 100 x 100 mm cubes in accordance with BS EN 12390-3:2009, and prisms of 100 x 100 x 500 mm were used for flexural strength. Results quoted in each case are the average of six specimens. As expected, the compressive strength of foamed concrete (FC) decreases with a reduction in density, but inclusion of MK resulted in improvement even at the low densities of (1300 and 1500) kg/m^3, see patches (S3 to S8) excluding S5 of Fig. (8). While S5 of (1200) kg/m^3 density with no MK inclusion showed the lowest compressive strength in comparison to S10 of (1300) kg/m^3, which are of close range densities.

Also, inclusion of MK at 50% showed improvement, compare patches (S9 and S10) of (1500 and 1300) kg/m^3 with S8 of (1800) kg/m^3 densities.

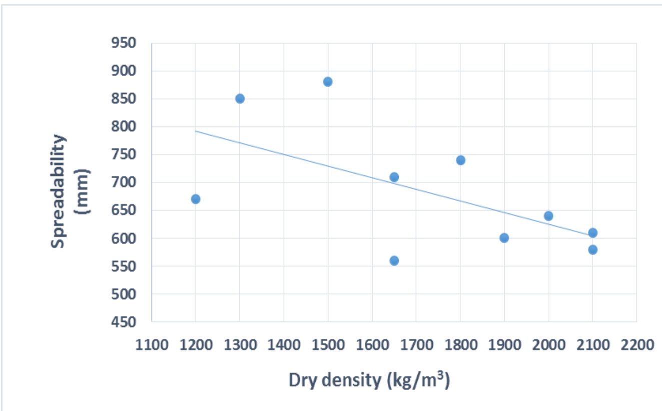

Fig. (7): Spreadability versus dry density for different types of concrete.

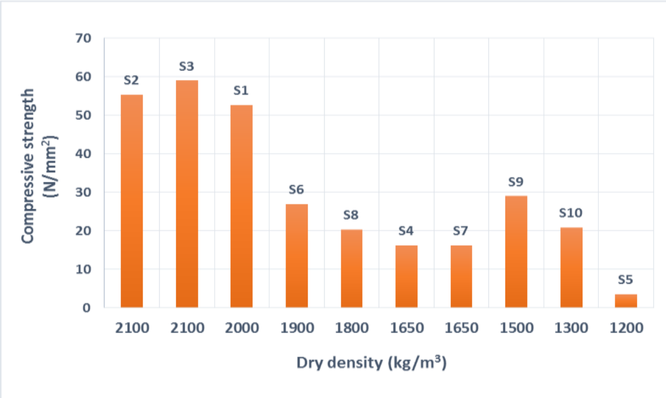

Fig. (8): Compressive strength versus dry density for different types of concrete.

Flexural Strength Test

Flexural strength test under four-point load was carried out according to BS EN 12390-5:2009. The test was performed only on six prisms, as shown in Fig. (9). Both (S1 and S3) specimens, having almost the same high density of (2000 and 2100) kg/m^3, but different flexural strength of (1.88 and 3.11) kN/mm^2 respectively. This difference is attributed to the higher MK inclusion at 20% for S3. Similarly, MK inclusion showed improvement in flexural strength for the rest of the tested specimens (S4, S9 and S10) having (2.5, 1.8 and 1.35) kN/mm^2 of (1650, 1500 and 1300) kg/m^3 densities respectively.

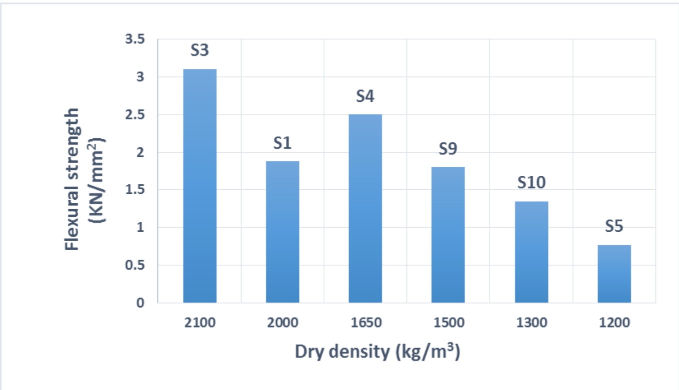

Fig. (9): Flexural strength versus dry density for different types of concrete.

Flexural Modulus

Flexural modulus was also worked out in accordance with BS EN 12390-5:2009, for the same six prisms tested for flexural strength. The high dosage of 50% MK inclusion, resulted in higher values of (7.0 and 6.6) kN/mm^2 for S3 and S9 of (2100 and 1500) kg/m^3 densities respectively. While at 20% MK inclusion, it was (6.3, 6.2, 3.5 and 1.9) kN/mm^2 for (S1, S4, S10 and S5) of (2000, 1650, 1300 and 1200) kg/m^3 densities respectively, see Fig. (10).

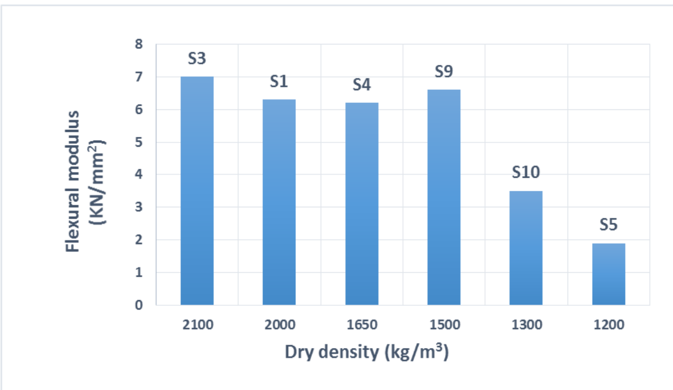

Fig. (10): Flexural modulus versus dry density for different types of concrete.

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Permeability Test

Permeability test through capillary water absorption under 5 bar pressure was carried out according to BS EN 12390-8:2009. Three oven dried specimens were put under the 5 bar pressure permeability test apparatus for 72 hours. After which, they were taken out and split open to mark and measure water penetration from bottom up in millimetres. Furthermore, total water absorption test was performed as per BS 1881-122:2011. Another three oven dried specimens were totally immersed in water for at least 72 hours. After which, they were taken out to measure the weight of absorbed water in (kg/m^3). The main purpose of these tests is to determine moisture movements and their related functions, for producing a water tight FC. In addition, specimens were observed for early thermal cracks and shrinkage crack types that could play a role in moisture movements and weakness of the concrete.

Figs. (11 and 12) show only specimens with the MK inclusion at 20%, namely, S3 a representative of normal concrete without foam and S6 a representative of foamed concrete. They demonstrated a better resistance to water penetration of both the 5 bar capillary and the total water absorption. Followed by (S1 and S2) of high densities and high compressive strength, finally, (S8 and S7), having Mk inclusion in their mixes.

Whereas, S9 and S10 of 50% MK inclusion, as well as (S4 and S5) which are of low densities, showed the worst case scenario in this connection, having the adverse effects for water permeability. Results show that permeability increases with the reduction in dry density, and when water reducing admixture has been used, also, when mixes contain high doses of MK, i.e. 50% MK.

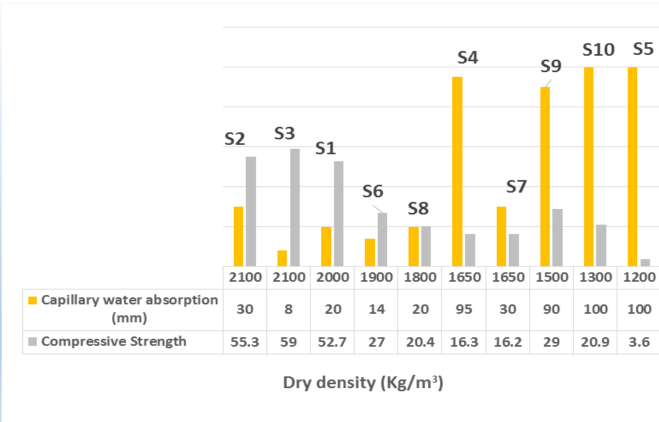

Fig. (11): Capillary water absorption versus compressive strength for different types of concrete.

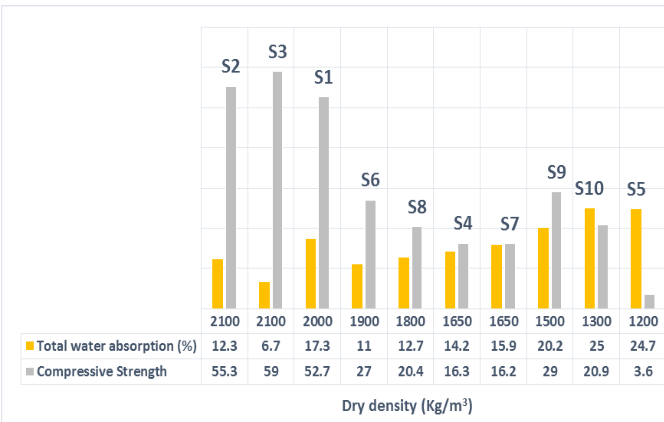

Fig. (12): Total water absorption versus compressive strength for different types of concrete.

Freeze and Thaw Test

Six cube specimens of each cast were undergone freeze and thaw test of 50 cycles between (+20 ^{o}C and -18 ^{o}C) with 90% humidity in accordance with BS EN 15304:2010. All of the cube specimens, SF1 to SF10 of Table (1) put under this test, showed (0.0 to 18%) differences in compressive strength in comparison with S1 to

S10 specimens which have not been subjected to this test, particularly with the MK at 20% inclusion, and only a few showed less strength. They hardly showed cracks or chipping of little bits and pieces, i.e. no fragmentations. This might be due to the good quality of the mixes, good curing regime and aging of the specimens. It is worthwhile mentioning that all the specimens meant for compressive strength were tested at the age of 28 days. On the other hand, those specimens meant for the freeze and thaw were tested at a more mature age of nearly 90 days, after undergoing 50 cycles of the freeze and thaw test, see Fig. (13).

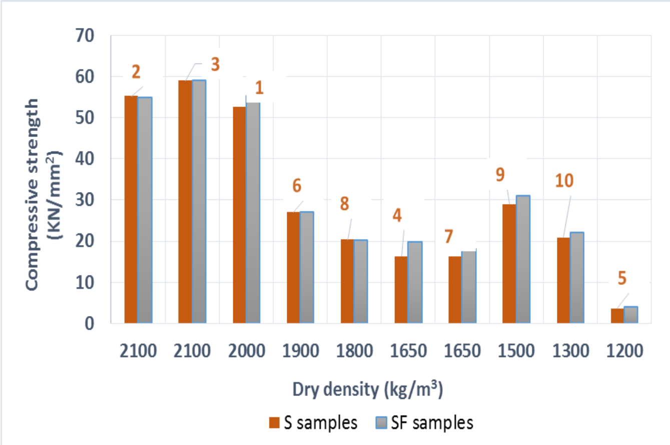

Fig. (13): Compressive strength of S samples versus SF samples for different types of concrete.

IV. CONCLUSIONS

The following conclusions can be drawn from the present study:

- Compressive strength is directly related to concrete density; concrete of high density exhibits high compressive and flexural strengths.
- MK at 20% inclusion improves compressive and flexural strengths as well as flexural modulus of the FC and normal concrete. Furthermore, MK at 20% inclusion improves other properties of foamed concrete as well as normal concrete, such as freeze and thaw, and water permeability of both capillary and total water absorption.
- The MK inclusion at 50% showed improvement to a certain degree for compressive and flexural strengths, and flexural modulus, as well as freeze and thaw process. But, it has an adverse effect on water permeability, particularly on the 5 bar capillary water absorption which proved to be very poor.
- Specimens subjected to freeze and thaw process of 50 cycles, showed no sign of deteriorations or any obvious change in the compressive strength. This indicates that the combination of the materials with the right proportioning of MK inclusion, and the chosen curing regime used for the specimens were appropriate and beneficial for developing the FC to have a good resistance in this respect, which is an indicative factor for durability.
- The water reducing admixture is incompatible with the foaming agent, therefore, it is recommended not to be used with the foamed concrete mixes.

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