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Effect of polypropylene fiber content on flexural strength of lightweight foamed concrete at ambient and elevated temperatures

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ABSTRACT

The impacts of volume fraction of polypropylene fiber (PF) on the bending behavior of lightweight foamed concrete (LFC) before and during exposing it to high temperature is experimentally studied. Five mixes of LFC with 600, 800, 1000, 1200 and 1400 kg/m^3 densities were made in current investigation. Then, the effect of adding PF with volume fraction of 0.1, 0.2, 0.3, 0.4, 0.45 and 0.5% on the flexural strength and pore structure of each considered density at ambient and elevated temperatures up to 600 ℃ was examined. The outcomes demonstrated that an increasing temperature had a detrimental influence on LFC property especially in a temperature range of 200 to 600 ℃ degrees in which flexural resistance was reduced by about 15 to 60% due to the micro diffusion of bound water molecules, detachment of the C-S-H gel and CH, weakness in chemical bond structure of cement paste and suppresses of the cohesive forces in the micropores. At each predetermined temperature, LFC with higher density achieved higher bending resistance as it had smaller and more uniform voids compared to LFC with lower density and higher loads were required to break it down. Adding PF by 0.1-0.4% of mix volume enabled LFC to resist high temperatures better than control plain concrete and the improvement percentage was directly correlated with PF content and LFC density. However, adding PF with volume fraction more than 0.4% reduced the flexural strength considerably. At ambient temperature, the larger content of PF led to an increased amount of pores in concrete structure and at elevated temperature a larger number of cracks were induced due to evaporation of more fibers and replacement of them by air voids led to significant reduction in flexural strength of LFC.

Keywords: Lightweight Foamed Concrete; Flexural Strength; Elevated Temperature; Polypropylene Fiber; Pore structure; Density; Fiber content; Void size

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INTRODUCTION

Over the last decades, a closed cell structure known as light weight foamed concrete (LFC) has been a very recognized material with its noticeable characteristics particularly in thermal insulation with a low thermal conductivity between 0.10 W/mK to 0.66 W/mK [1] and a typical density of 400-1600 kg/m^3 [2]. It consists of a cement paste with at least 20% by volume homogeneous pore structure induced by entering air in the form of small bubbles [3, 4]. Most of the air voids in LFC are disconnected[5], which curb the heat flow by restricting the movement of air and provide a high thermal resistance composition[1,6]. Accordingly, foam concrete is applicable to structures where fire is a risk like firewall [7] and its behavior at high temperatures should precisely be investigated.

Thus far, most of the research [8,9,10,11] on deterioration of high temperature exposed concrete are carried out on compressive strength characteristic as it is considered the main property of concrete and also the tensile strength test is difficult to perform. However, it has been distinguished that; at elevated temperature, tensile strength of concrete is a better parameter for damage and failure criteria of deteriorating and spalling behavior of concrete is highly and primarily influenced by tensile strength [12]. Since, spalling is caused by internal water pressure at about 300 °C and during dehydration of hydrated calcium silicate hydrate which increases internal stresses and induce microcracks [13], then the incorporation of fibers can relieves the pressure and improve spalling resistance of concrete [14, 15]. According to Bilodeau et al [16] the most effective spall-mitigation fiber which has been used so far is polypropylene fiber (PF). Theoretically PF has a relatively high melting point of 160-170 °C due to the presence of atactic material and non-crystalline regions which provides resistance to softening at high temperatures [17, 18, 19]. Melting of PFs creates more exit lines for water to escape the composite and leads to improvement in the flexural strength of concrete by reduction in the internal stress and explosive spalling. Liu et al [20] indicated that the melting of the PF increased the interconnection of pores leading to an increase in permeability. Higher permeability enhances concrete behavior exposed to high temperature, with lower possibility of spalling.

Beneficial incorporation of PF on LFC properties at ambient temperature also has been reported by some researchers. Kearsely [21] noted that the use of PF enhances the performance with respect to tensile and flexural strength of LFC. Bing et al [22] examined the properties of high-strength foamed concrete and concluded that in addition to tensile strength, PF greatly improved the compressive strength and drying shrinkage resistance of LFC.

Mao-hua Zhang and Hui Li [23] as well as Josef et al [24] reported that with the addition of PFs, the formation of microcracks is prevented and the scale of microcracks is reduced due to the crack-arresting effect, crack thinning effect and crack-bridging effect of PF. Similarly Ahmed et al [25] affirm that tensile and flexural strength is increased through bridging mechanism of PF. It is also concluded that adding PF to concrete up to a certain ration improves concrete propitiates and after that it reduced the bond strength between concrete ingredients and results in quick failure compared to less volume of fibers.

Some investigations have been conducted to estimate an optimum dosage of PF which improves the flexural strength and reduces or prevents spalling at high temperature. Ramamurthy et al [2] suggested chopped PFs of 12 mm length in the dosage range of 1–3 kg/m³ to enhance the shear behaviour of LFC equivalent to that of normal concrete. At higher temperature also higher PF content increases the residual strength of concrete due to increase in crack arresting ability by the presence of more PFs. In the experimental research of Cheon-Goo Han et al [26] it was observed that the spalling did not occur in any of the specimens when PF percentage was more than 0.45 kg/m³ while the plain concrete mixes suffered severe spalling damage. Guncheol Lee et al [27] observed a surface spalling in specimen contain PF with a percent content below 0.075% while specimens with contents of more than 0.1% of PF could prevent spalling damage.

However, a certain PF content which effectively increases in LFC flexural strength due to restraining and bridging the cracks at ambient temperature and reduction of spalling by increasing the permeability at higher temperatures has not been verified yet. Nevertheless, this paper aims to investigate the effect of different PF contents on flexural strength of LFC at both ambient and elevated temperatures. In the experimental part of this research, LFC with densities of 600, 800, 1000, 1200 and 1400 kg/m³ will be manufactured.

For each density, effect of adding PF by 0.1%, 0.2%, 0.3%, 0.4%, 0.45% and 0.5% of mix volume and in a temperature range of 20 to 600 °C on flexural strength and pore structure of LFC will be examined. Later, experimental results of all series will be compared with each other and then will be compared with the plain LFC to find an optimum value of PF content in which bending strength of LFC has the highest percentage of improvement.

MATERIALS AND METHODS

LFC were made of cement, water, filler and a liquid chemical diluted with water and aerated to form the foaming agent. The foaming agent was diluted with water with a ratio of 1:33 by volume. A constant cement-sand ratio of 1:1.5 and water-cement ratio of 0.45 for all mixes were excogitated. All the applied materials in the experiment were Malaysian local productions. The type of the applied cement in all admixtures was Type I ordinary Portland Cement CEM1 (Blue Lion trademark), which is available in bulk form 50kg packs and complied with MS522 and BSEN 196. The employed cement quality in this research is demonstrated in table 1. Detailed properties and specifications on each substance used in this experimental investigation are presented at Table 2. LFC with 600, 800, 1000, 1200 and 1400 kg/m³ densities were fabricated and tested. The protein foaming agent used in the experiment, is known as NORAITE PA-1 consists of additive agent and extracted from natural sources and befitting LFC densities ranging from 600 to 1600 kg/m³.

Table 1. Properties of Portland Cement CEM1

Item	Clinker %	Cement %
Oxide composition		
SiO_2	21.04	19.98
Al_2O_3	5.24	5.17
Fe_2O_3	3.41	3.27
CaO	63.31	63.17
MgO	0.85	0.79
SO_3	0.41	2.38
Total Alkalis	0.9	0.9
Insoluble residue	0	0.2
Modulus		
Lime saturation factor	0.93	0.96
Silica modulus	2.39	2.37
Iron modulus	1.9	1.58
Mineral composition (%)		
C_3S	55.4	59.9
C_2S	18.53	12.71
C_3A	8.59	8.18
C_4AF	10.36	9.94
Free CaO (lime)	1.9	0

2.1. Specimen preparation

A mixture of the liquid protein and water in a tank was connected by a hose to the foam generator. The foam generator type was Portafoam TM2 System, made by Malaysian manufacturer as illustrated in Figure 1. The foam density output and flow rate were the results of this system operation. The flow test was performed when all the materials were mixed well in a drum mixer. When the mortar achieved the desired spread, the mortar density was measured. Then, according to the machine flow rate, the required foam amount was calculated and added to the mix. The fiber was added to the mix after the flow test and before the mortar density measurement. Promptly after mixing, the concrete was placed in moulds in order to prevent breaking down of the air bubbles before it was set. At about 24 hours after that, concrete moulds were removed and three specimens were considered for each density and examined at the age of 28 days.

Table 2. Properties of additives used

Size	19mm length
Specific gravity	0.90 kg/dm^3
Material	100% virgin polypropylene
E- modulus	3900 N/mm^2
Chemical composition	C-33% H- 67%

Figure 1. Portafoam TM2 foam generator system.

2.2 Heating of specimens

Two types of furnaces were employed in order to heat the specimens including low temperature electric furnace and high temperature electric furnace with a maximum operating temperature of 450 and 1000 °C respectively. During the experiment, three samples were hold in each furnace and temperature was kept within ±1 °C over the test range. Then, bending resistance test was carried out at predetermined temperatures of 20, 100, 200, 300, 400, 500, and 600°C. Flexural strength test of LFC specimens at 20 °C were conducted at room temperature. The temperatures of

100 to 400 degrees were applied at specimens in low temperature furnace and other specimens were heated up to 600 °C degrees in high temperature electric furnace. Figure 2 was provided to show an electric furnace used to heat LFC specimens.

Figure 2. Heating of LFC specimens in an electric furnace to predetermined temperatures

2.3 Three point bending test overview

Flexural testing was used to determine the bending properties of LFC while the specimen temperature was kept constant. Rectangular parallelepipeds of height (h) 25 mm, width (w) 125 mm and length L (l) 350 mm dimensions were placed on two supports with 200mm length between them and a load at the midpoint of the samples was initiated in the way that is presented in Figure 3 and Figure 4. Maximum stress and strain were calculated on the incremental load applied for the evaluation of bending strength.

Figure 3. Set up for three point bending test

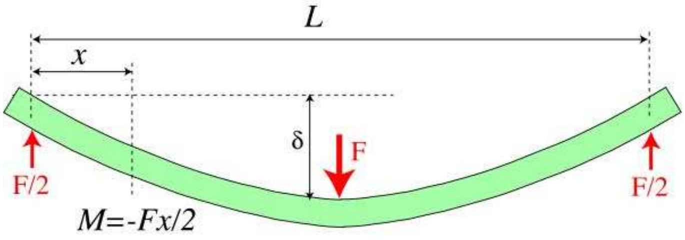


Figure 4. Simply supported specimen subjected to a concentrated load at mid span

2.4. Measurement of Void Size

Initiating a void size for each density is essential to analyse the pore size effect on flexural strength of foamed concrete. Similar techniques under the same environmental condition were used for all the specimens to ensure the results to be accurate. All specimens were vacuum-impregnated with slow-setting paste. A diamond cutter was used to slice two randomly chosen 100 mm cubes to obtain the specimens of 45 x 45 mm size with a minimum thickness of 15 mm. The specimen face was cut vertically according to the mold direction. In order to prevent more hydration reaction, the specimens were impregnated in acetone before drying at 105 °C. The dried and cooled specimens were vacuum saturated with slow-setting epoxy to certify the consistency of the air-pore walls during polishing. The imbrued specimens were varnished as per ASTM C 457. the specimens were dried at ambient temperature for 24 hours after polishing and cleaning them. Finally, an effective size 40 x 40 mm was noticed for evaluation of void size.

RESULTS AND DISCUSSION

i. Effect of temperature on flexural strength of foamed concrete

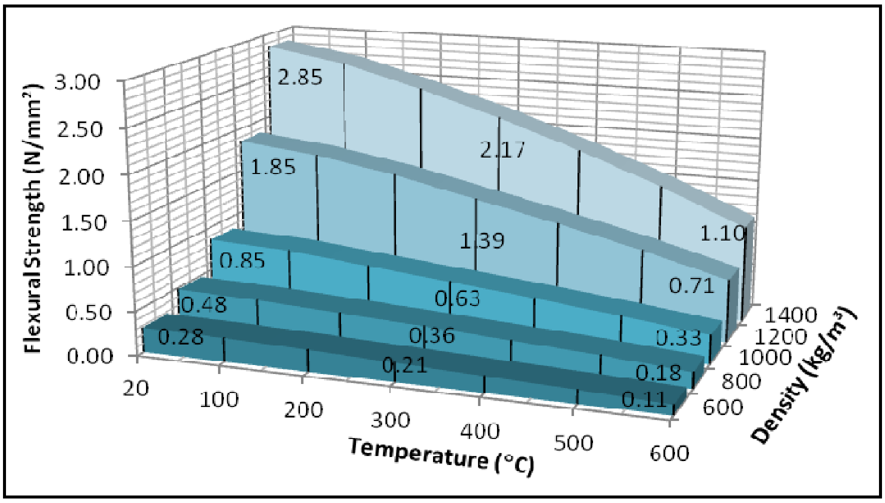


Figure 5. Flexural tensile strength of control LFC as a function of temperature

Flexural responses of control LFC before and after exposure to high temperature are given in Figure 5. According to the experimental results, bending resistance of LFCs with densities ranges of 600-1400 kg/m³ varied from 0.28 to 2.85N/mm² at ambient temperature. In addition, the flexural strength of all series reduced with the increasing of the temperatures. At temperatures above 90° C, calcium oxide was formed due to the dehydration of calcium hydroxide Ca(OH)2. Then, the chemically bound water molecules were scattered to the capillary pores and created the initial micro cracks. These microcracks were expanded adjacent the un-hydrated cement particles and lead to reduction in bending strength of concrete as it is negatively influenced by cracks. This reduction continued slowly and LFC lost 15% of its strength until reaching the temperature of 200 °C degree. The effect was more conspicuous at temperatures above 200 °C since the majority of the cracks and the large cracks were induced at higher temperatures.

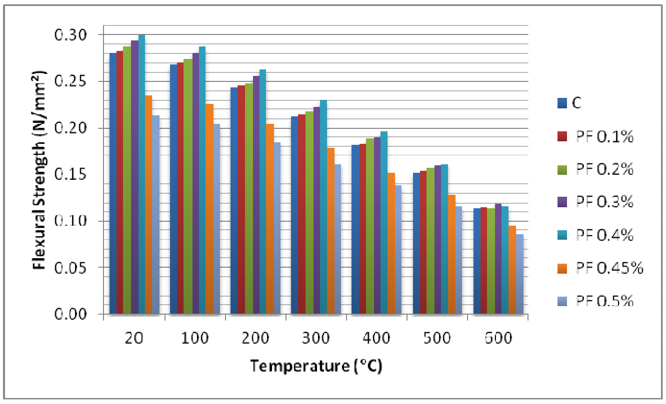
At temperatures around 300 and 400 °C degree, flexural strength was reduced by about 25 and 35% as a result of rapid decomposition of C-S-H gel and generation of a high pore pressure in composite. Since LFC has a low permeability, created pressure lead to the formation of harmful cracks around Ca(OH)2 crystals and unhydrated large cement grains as it cannot be revealed sufficiently. Eventually, the micro diffusion of bound water molecules, along with detachment of the C-S-H gel and CH, diminishes in chemical bond structure of cement paste and suppress the cohesive forces in the micropores and led to reduction in strength by about 50% and 60% at 500 and 600 °C respectively. Much later in exposure to the higher temperatures, the ultimate tensile strength of concrete can be reached and will cause the collapse of pieces of LFC.

ii. Effect of fiber content on flexural strength of foamed concrete

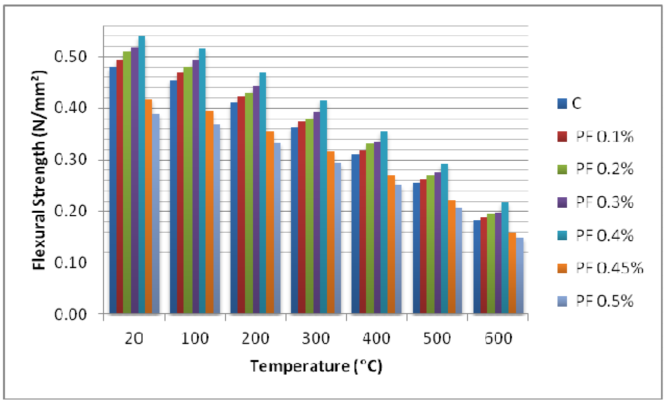
The elevated temperature flexural strength of LFC incorporating different PF content are presented in Figure 6. The results indicated a reduction in flexural strength for both the plain LFC and PF reinforced LFC with increasing temperature. However, addition of PF up to a certain value of 0.4% of mix volume enabled LFC to resist high temperatures better compared to control plain concrete at all applied temperatures. Adding 0.1, 0.2, 0.3 and 0.4% of mix volume PF to LFC with different densities in a range of 600-1400 kg/m³, improved bending strength by about 1-14%, 3-20%, 5-22% and 7-26% respectively. Improvement percentage was directly proportional to LFC density in such a way that; LFC with higher density had higher improvement percentage.

Normally, microcracks are created in concrete from thermal stresses, drying shrinkage, steam generation and slipped or splitting of the concrete. However, it is the additional formation of microcracks by the melting of the PFs which acts alongside with these pores to facilitate the passage of water vapor through the concrete and improve concrete protection level against explosive spalling.

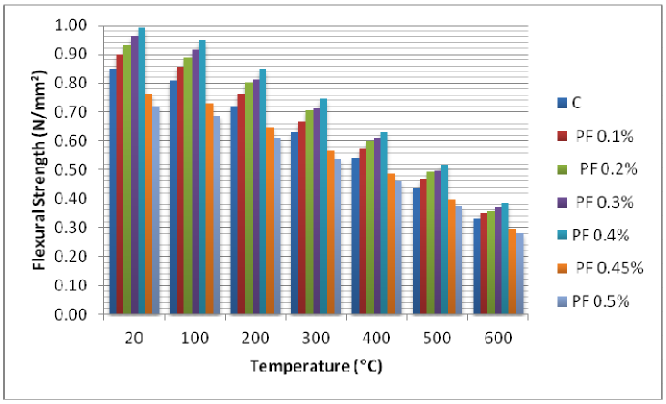
Thus, the capability of fiber in spalling protection is owing to its ability in pores interconnection through melting process at elevated temperatures. Evidently, a higher number of fibers increase the possibility of pores connections in the network by producing a higher stress and increasing the tendency of microcrack formation as a result of this stress. However, in the case of PF, having a melting point of 160-170 °C, permitted a spalling protection with considering less fiber content as it was observed after a certain level, flexural strength started dropping with increasing PF content by 0.45 and 0.5% of mix volume by about 4-16% and 8-24% respectively. Declination percentage was inversely proportional with LFC density, which means LFC with higher density had lower dropping percentage and vice versa. Evaporation of more fibers at elevated temperature and replacement of them by air voids created a larger number of cracks which caused the PF reinforced LFC to lose most of its ability to resist loads.



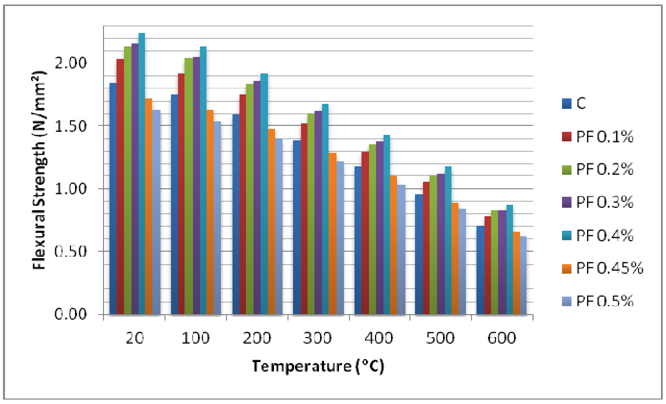
6(a) 600 kg/m³



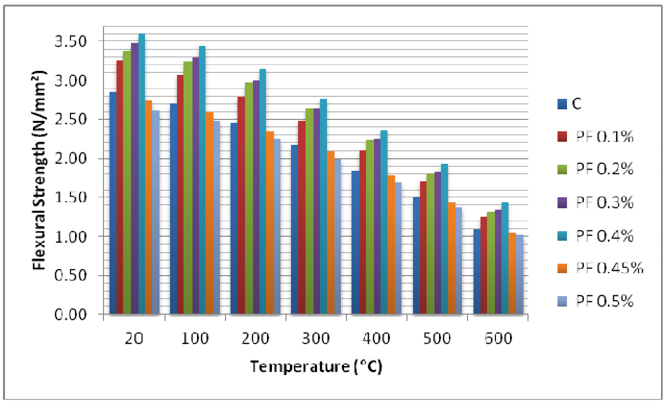
6(b) 800 kg/m³



6(c) 1000 kg/m³



6(d) 1200 kg/m³



6(e) 1400 kg/m³

Figure 6. The elevated temperature flexural strength of LFC made by different compositions

iii. Effect of density on flexural strength of foamed concrete

Flexural strength of LFC with different densities is shown in Figure 7. It can be clearly seen that LFC flexural strength is directly correlated to its density in such a way that; flexural strength increases with increasing the foamed concrete density. By each 200 kg/m³ addition in density, the flexural strength increased by 1.5 to 2 times its value, regardless to temperature. As density of LFC decreases, the value of air bubbles and the interconnection of them increases significantly. Therefore, water vapor permeability increases and lead to reduction in LFC strength. In LFC with higher density the cellular solid structure is different; cell walls are thicker and pore spaces are smaller and isolated. With increasing the density air voids are transformed to solid structures, thus, more applied loads are required to fail the sample.

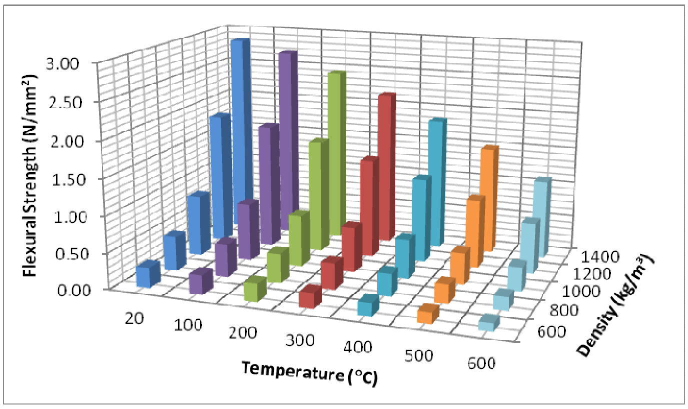


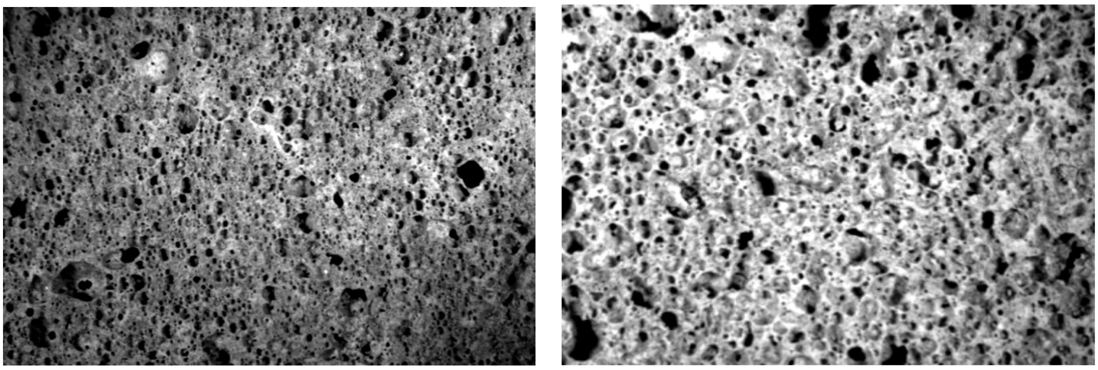
Figure 7. Flexural tensile strength of control LFC with different densities

iv. Effect of void size on flexural strength of foamed concrete

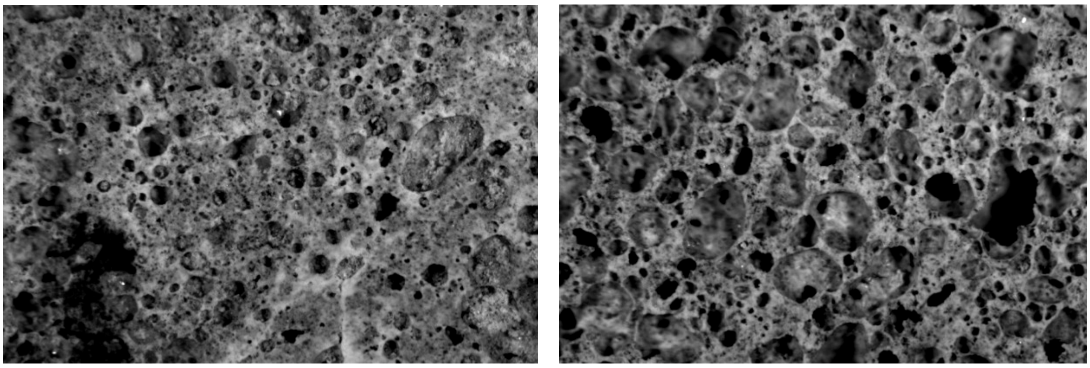
Generally, mechanical characteristic of a material is influenced by its micro-structural features. The pore structure is one of the main micro structural properties affecting the strength capability of concrete and it is recognized by porosity, mean radius and pore size distribution in the composite. Figure 8 shows typical microscopic images of the internal pore structure of plain LFC with densities of 600, 800, 1200 and 1400 kg/m^3 at the temperature of 20 °C. It is appear that for lower densities there is an increase in the number of larger voids while the voids are smaller and more uniform in size in LFC with higher densities.

LFCs with lower densities have a larger volume of air voids which results in higher porosities. In addition, the air bubbles are close together just after casting and therefore have the high chance to be connected before setting of the cement around them. Induced large voids adversely affect the LFC flexural strength since this property of concrete is so sensitive to voids and cavities. As a result, compared to LFC with 800, 1200 and 1400 kg/m³ densities, LFC with 600 kg/m³ density has 14, 55 and 74 % higher void size and 44, 86 and 92% lower flexural strength respectively. In higher densities, the air voids are not near to each other in the paste and therefore do not have the opportunity to make a network before paste is set around them. Since strength is inversely correlated with the mean distribution radius, reduction in void size increase the strength of composite and when the numbers of smaller voids are dominant, strengths is increased due to the greater number of hydrated phases.

From Figure 9 which illustrates the microstructure image of LFC with 800 kg/m^3 density incorporating 0.2 and 0.4% PF, it is clearly seen that adding PF increases void volume in concrete. The effect of PF addition on concrete properties enhance with fiber content, unless the fiber content is so high that the air void content becomes exceedingly high. Larger the content of PF lead to the coarser the pore structure of concrete and lower the durability. The addition of PF is detrimental to concrete impermeability as the permeability of concrete containing PF enhances due to increase the void content in concrete and the lack of cohesiveness of cement matrix and poor dispersion of PFs. Improvement in dispersion and proper interfacial adhesion of PFs in cement mix causes a mark reduction in the permeabiliy of PF reinforced LFC.

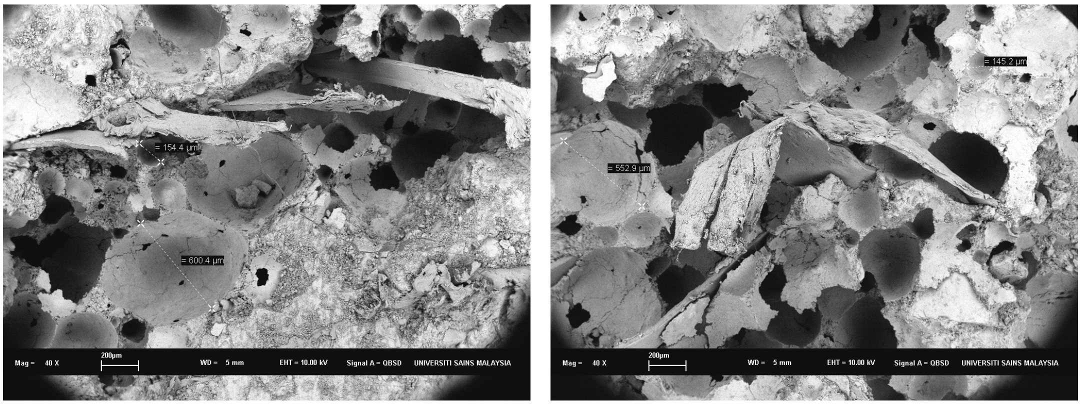


(a) 1400 kg/m^3 density with 0.42mm void size **(b) 1200 kg/m^3 density with 0.47mm void size**



(c) 800 kg/m^3 density with 0.64mm void size **(d) 600 kg/m^3 density with 0.73mm void size**

Figure 8: Void sizes for different densities of lightweight foam concrete



(a) 0.20% fiber **(a) 0.40% fiber**

Figure 9. Addition of fiber which results in production of pore and cavities that surround area of fiber for 800 kg/m^3 density

CONCLUSION

The bending behavior of high temperature exposed LFC incorporating different PF percentages in range of 0.1 to 0.5% of mix volume was investigated. Flexural strength test was conducted on LFC with density range of 600 to 1400. Then, the effects of temperature, density, PF content and pore structure on the properties of LFC containing PF were investigated. The following conclusions are drawn from this study:

1. At ambient temperature, bending resistance of LFCs with densities ranges of 600-1400 kg/m³ varied from 0.28 to 2.85N/mm². At temperatures above 90° C, initial micro cracks were induced due to dehydration of Ca(OH)2 and LFC lost 15% of its strength at 200 °C. At temperatures of 300 and 400 °C degree, flexural strength was reduced by about 25 and 35% as a result of rapid decomposition of C-S-H gel and creation of a high pore pressure in composite. Increasing the temperature weaken the chemical bond structure and suppress the cohesive forces in the micropores and reduced the strength by about 50% and 60% at 500 and 600°C respectively.
2. Addition of PF up to 0.4% improved LFC bending resistance. Adding PF with volume fraction of 0.1, 0.2, 0.3 and 0.4% to LFC with densities range of 600-1400 kg/m³, improved bending strength by about 1-14%, 3-20%, 5-22% and 7-26% respectively. LFC with higher density had higher improvement percentage. The flexural strength decreased about 4-16% and 8-24% with adding PF with volume fraction of 0.45 and 0.5% as more fibers were evaporated and replaced with air voids and a larger number of cracks were induced in LFC at elevated temperature.
3. Flexural strength increases with increasing the foamed concrete density. By each 200 kg/m³ addition in density, the flexural strength increased by 1.5 to 2 times its value, regardless to temperature. With increasing the density air voids are transformed to solid structures, thus, more applied loads are required to fail the sample.
4. There is an increase in the number of larger voids for LFC with low densities while the voids are smaller and more uniform in size in LFC with higher densities. Reduction in void size increases the strength of composite due to the greater number of hydrated phases. However, unlike high density LFC, in LFCs with lower densities the air bubbles are close together after casting and can be connected to make larger voids and adversely affect the LFC strength.
5. Larger the content of PF lead to the coarser the pore structure of concrete and increase LFC permeability due to increase the void content in concrete and the lack of cohesiveness of cement matrix and poor dispersion of PFs.

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