



Influence of High Temperatures on Flexural Strength of Foamed Concrete Containing Fly Ash and Polypropylene Fiber

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ABSTRACT

In this study, the high temperature flexural strengths of lightweight foamed concrete (LFC) containing fly ash (FA) and polypropylene fiber (PF) was investigated experimentally and statistically. The variables included were temperature (in the range 20 to 600°C), LFC densities of 600, 800, 1000, 1200 and 1400 kg/m³ and additive content. Two mixes were made by replacing 15% and 30% of cement mass with FA. In another two series 0.2vol% and 0.4vol% of PF was added to LFC mix, and finally, one controlled mixture without additives was produced. After being subjected to high temperatures, the flexural strengths of LFC were investigated. The reduction of LFC flexural strength at high temperature may be principally due to the formation of micro cracks at temperatures above 93°C, since the flexural strength is adversely influenced by cracks so that a severe strength loss was observed at 600°C and the flexural strength was only about 40% of its original value. Flexural strength of LFC with higher density achieved a higher value regardless to temperature. LFC flexural strength exposed to high temperature increased by contribution of FA and PF and this relative improvement for all series was the most pronounced for LFC with higher density and higher additive content. In addition, the applicability of some suggested models for normal concrete was examined for the flexural strength prediction of LFC incorporating different percentages of FA and PF at high temperature and the most reliable model was recommended for future researches.

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NOMENCLATURE

$f_{cr,T}$	Tensile strength of concrete at high temperature	T	Temperature in °C
f_{cr}	Tensile strength of concrete at ambient temperature	ρ	Density (kg/m ³)

1. INTRODUCTION

At present, the construction industry has shown significant awareness in utilizing lightweight foamed concrete (LFC) as a building material. The demand of LFC is becoming higher now where this material has increased several folds in recent years due to its inherent economic and other advantages over conventional concrete in a range of structural and semi-structural applications. The major specialties of LFC are its excellent thermal conductivity, low self-weight, high impact resistance and good freeze thaw resistance. With appropriate control in amount of foam and methods of production, a wide range of densities (400 – 1600 kg/m³) of LFC could be produced hence providing

flexibility for application such as structural elements, partition, insulating materials and filling grades. LFC has a self-levelling and self-compacting nature physically where it fills the smallest voids, cavities and seams within the pouring area. LFC is a complex material, which acts in appropriately complex way. Its properties diverge with age, temperature and humidity.

LFC is a type of aerated concrete in which the aerating agent is either protein or synthetic foam using foam generator [1]. The high air contents result in higher porosities, lower strengths and lower densities [2]. LFC provides an excellent acoustic and thermal insulation and can be used as partition or load-bearing wall in low-rise residential buildings [3]. In building designs, one of the main safety requirements is preparation of pertinent fire safety. For this purpose, LFC should be approved to have a high resistance at high temperatures since the structural members are the

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final line of deterrence when other measures for extinguishing the fire fail.

The degradation mechanisms of LFC at high temperatures include chemical degradation and mechanical deterioration. The dehydration process in the cement is considerable at temperatures above 110°C. At higher temperature about 300°C the internal water pressure increases the internal tensile stresses and causes expansion of the cracks [4, 5]. Existence of cracks caused by high temperature leads to reduction of LFC strength. However, cracking influences more severely the flexural strength than the compressive strength [6, 7] since the flexural strength is more sensitive to cracks caused by high temperatures to concrete [8]. At high temperature flexural strength continued to decrease due to the elimination of bound water, corresponding to a large mass loss [9]. There have been few reported investigations on the flexural behavior of LFC at high temperature. Othuman Mydin and Wang [10] carried out a research on mechanical properties of LFC subjected to high temperatures. In their research, flexural strength of LFC reduced mainly after 90°C. It was concluded that micro cracking is the primary mechanism that causes degradation, which occurs as the free water and chemically bound water evaporates from the porous body.

Song et al [11] concluded that crack control played a vital role in performance life of concrete structure. Concerning the crack control, the incorporation of discrete fibers into vulnerable concrete was useful and effective [12]. For decades, fibers have been extensively used to improve ductility of concrete [13, 14].

According to Sing et al. [15] fibers were increasingly used for reinforcement of cementitious matrix to improve the toughness and energy-absorption capacity and to reduce the cracking sensitivity of the matrix. At present, it is distinguished that there are a few types of fibre which can also improve the residual characteristic of concrete exposed to high temperatures [16]. Several studies have shown that the thermal stability of concrete is improved by incorporating polypropylene fibers (PF) into the mix [17, 18]. PFs have been used to considerably reduce the amount of spalling effect and cracking whilst enhance the residual strength [19, 20]. The micro PFs decrease the shrinkage micro cracks before heating and reduce the spalling [21] at the high temperature. However, minimal or detrimental effects of the PFs on the residual behavior of the heated concrete were also observed. Several studies [14, 22] showed that there was a reduction in the strength, caused by the additional voids; while other researchers showed that there was an improvement in the residual strength [17, 19, 23]. The difference between the results can be related to the test conditions, curing methods and the heating rate. Mirza and Soroushian [24] conducted an experiment on PF

reinforcement on lightweight concrete. They found that it had a possibility to increase the flexibility of lightweight concrete. Sinica et al. [25] found that introducing carbon fibers with filament, which were 5mm long and with a diameter of 4.6-7.7 mm, had a positive effect on the flexural strength of non-autoclaved foamed concrete. The flexural strength of specimens increased by 24.5%. LFC has also a potential for large scale utilization of wastes like fly ash (FA). The advantageous contribution of FA on high temperature resistance of concrete has been proved by several researches [26 - 28]. At high temperatures, the compressive and splitting tensile strength loss in concrete containing FA is less than that of concrete made by ordinary Portland Cement CEM1. It shows that FA contributes to the interfacial properties mainly by the pozzolanic effect [29]. The increase in strength can be caused by the high strength ceramic bonds that created due to thermo-chemical reactions at high temperatures [30]. In addition, FA reduces the surface cracking of concrete both at high temperature and after post-cooling in air or water [28]. There is a lack of information on thermal properties of LFC contain additives at high temperature since the most of researches were carried out on LFC properties at ambient temperature. However, it is proved that, 30% cement replacement by FA reduces thermal conductivity of LFC by 12–38% due to the lower density and cenospheric particle morphology of FA particles, which increases the heat flow path [31]. In general, the addition of FA contributed more or less to the residual strength of concrete for all the concrete mixes and the beneficial influence of FA can be ascribed to the pozzolanic reaction consuming $\text{Ca}(\text{OH})_2$ in the hydrates [27].

Therefore, the primary objective of this research is to investigate the effect of high temperature on the flexural strength of LFC incorporating FA and PF. Tests will be conducted at predetermined temperatures of 20, 100, 200, 300, 400, 500, and 600°C on LFC with densities of 600, 800, 1000, 1200 and 1400 kg/m^3 . Five different mixes will be manufactured for each density; plain LFC is made as a controller, two mixes will be made by replacing 15% and 30% of cement mass with FA and in other two series, PF will be added to LFC mix, by 0.2% and 0.4% of binder volume. In mix design a constant water-cement ratio of 0.45 and cement-sand ratio of 1:1.5 will be considered for all series. Later, test results will be compared with proposed models for normal concrete and the prediction equation, which is in the best agreement with test results, will be suggested.

2. MATERIAL AND MIX PROPORTION

LFC was produced under controlled condition from cement, water and a liquid chemical that is diluted with

water with a volume ratio of 1:33 by water and aerated to form foaming agent. The cement used for all admixtures in this research is Type I ordinary Portland Cement CEM1, produced by CIMA and is packed under the brand name "Blue Lion" Cement. It is available in 50kg packs and in bulk form and complies with MS522 as well as BSEN 196. Table 1 shows the quality of the cement used in this study. FA and PF were also used with different percentages. All of the materials used were produced locally in Malaysia. Table 2 gives detailed properties and specifications on each material used in this experimental investigation.

LFC with 600, 800, 1000, 1200 and 1400 kg/m³ densities were manufactured and tested. The protein foaming agent was used, known as NORAITE PA-1, which comes from natural sources and is appropriate for LFC densities ranging from 600 kg/m³ to 1600 kg/m³.

2. 1. Specimen Preparation The liquid protein was mixed with water in a tank and then it was connected to the foam generator by hose. The foam generator used in this research, was Portafoam TM2 System, made by Malaysian manufacturer (www.portafoam.com) as shown in Figure 1.

TABLE 1. Properties of Portland Cement CEM1.

Item	Clinker %	Cement %
Oxide Composition		
SiO ₂	21.04	19.98
Al ₂ O ₃	5.24	5.17
Fe ₂ O 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
LOI	0.5	2.5
Modulus		
Lime saturation factor	0.93	0.96
Silica modulus	2.39	2.37
Iron modulus	1.9	1.58
Mineral Composition (%)		
C ₃ S	55.4	59.9
C ₂ S	18.53	12.71
C ₃ A	8.59	8.18
C ₄ AF	10.36	9.94
Free CaO (lime)	1.9	0

TABLE 2. Properties of fly ash and polypropylene fiber

	FA	PF
Size	5µm to 100µm	19mm length
Specific gravity	2.3	0.90 kg/dm ³
Material	Waste from electricity	100% virgin polypropylene
E- modulus	-	3900 N/mm ²
Chemical composition	SiO ₂	C-33%
	Al ₂ O ₃	H- 67%
	Fe ₂ O ₃	
	CaO	
	MgO	
	SO ₃	
	Na ₂ O	



Figure 1. Portafoam TM2 foam generator system

This system was then tested to achieve the foam density output and flow rate. The flow test was carried out after all the materials were poured and well mixed in the drum mixer. The mortar density was measured when the mortar achieved the desired spread. The amount of required foam was then calculated from the machine flow rate and was added to the mix. The method and calculation of mixing for LFC incorporating either FA or PF was the same as normal mix except that fiber was only poured into the mix after the flow test but before the mortar density measurement. After the mixing process, the LFC slurry was immediately placed in the mould to prevent breaking down of the air bubbles. After 24 hours, the hardened LFC samples were demoulded. Three specimens were provided for each density and were tested at the age of 28 days.

2. 2. Heating of Specimens The flexural strength tests were conducted at about 20, 100, 200, 300, 400, 500, and 600°C on LFC with different densities. The temperatures up to 400° C were applied to specimens using a low temperature electric furnace which covers a temperature range of 50-450°C.



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



Figure 3. Set up for three point bending test

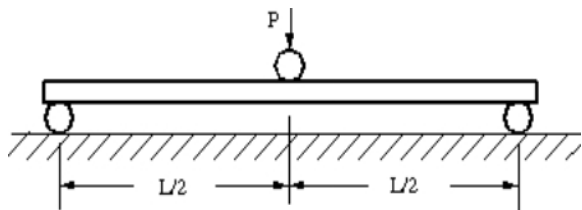


Figure 4. Simply supported specimen subjected to a concentrated load at mid span

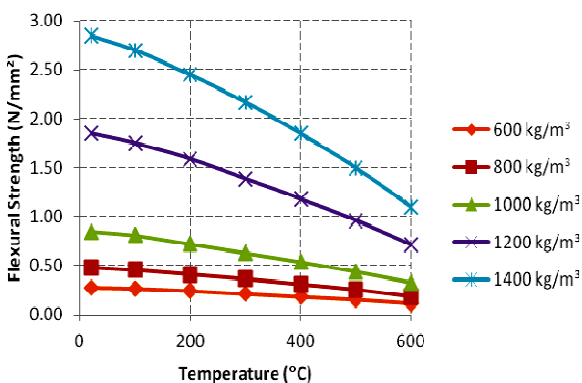


Figure 5. Flexural tensile strength of control LFC as a function of temperature

Another furnace which had a maximum operating temperature of 1000 °C was used for exposing concrete specimens to 500°C and 600°C as been shown in Figure 2. Both furnaces were capable of holding three specimens and could maintain furnace operating temperatures within ± 1 °C over the test range.

2. 3. Three Point Bending Test Overview In bending strength test, loading without shock were applied and increased gradually at a nominal rate until failure while the specimen temperature was kept constant at a predetermined temperature. This test performed on rectangular parallelepipeds of height (h) 25 mm, width (w) 125 mm and length L (l) 350 mm dimensions. As can be seen in Figure 3 and Figure 4, the specimen was simply supported with 200mm length between supports and a point load was applied at the centre. The load–deflection was recorded for the evaluation of flexural tensile strength.

3. RESULT AND DISCUSSION

3. 1. Effect of Temperature on Flexural Strength of LFC For all densities, the LFC flexural strength decreased with temperature. Figure 5 shows the flexural strength of control LFC at different temperatures. Initial heating of all series caused delayed ettringite formation which occurs at temperatures above 65°C and generates destructive distensible forces in the concrete. Physical and chemical changes and slight volume changes - usually shrinkage- occur between 93 and 200 °C when evaporation of the free moisture contained in the concrete mass occurs. As a result, at 200 °C flexural strength of all series, reduced to 85% of its original value. At a temperature of 200-300°C, dehydration caused decomposition of the C-S-H and sulfoaluminate phases and surface hairline cracks begin to form. Bending strength of concrete is adversely influenced by cracks -either on macro or on micro scale- which are caused by high temperatures. As a result, all series lost about 25% of their original flexural strength value at this stage since existence of these cracks reduced the effective cross-sectional area, and the tensile stress caused expansion of the cracks and cracking. At 400°C flexural strength was about 65% of the initial value for all densities. Temperatures in the 500°C range are critical because calcium hydroxide dehydrates at that temperature and deep cracks have begun to be formed which result in the disintegration of the concrete. At 600°C flexural strength was about 40% of the original value for all densities.

3. 2. Effect of Density on Flexural Strength of LFC Figure 6 presents the flexural strength of control LFC

with different densities at each applied temperature ranging from 20° C to 600° C. At each predetermined temperature, flexural strength of LFC with higher density achieved a higher value e.g the flexural strength of LFC with 800, 1000, 1200 and 1400 kg/m³ densities are respectively about 2, 3, 6.5 and 10 times higher than that of 600 kg/m³ density at all temperature degrees.

In LFC, density can be controlled by introducing air in foaming process. Occupying space between the cement particles create more porous cement, increase the air void values and eventually lead to reduction of hardened concrete density. Lower density LFC exhibit a more open microstructure compared to higher density mixes of the same mix constituents and they contain greater volume of air bubbles. According to the fact that the strength of concrete is adversely influenced by the existence of voids in the concrete it is concluded that, for a given cement combination and content, at equal water/ binder ratio, the lower density LFC with greater air contents will have a lower flexural strength.

3. 3. Effect of Additive on Flexural Strength of LFC

3. 3. 1. Fly Ash (FA) At high temperature calcium hydroxide conversion into lime and water vapor is not critical concerning strength loss whereas it may cause serious damage in cooling period due to the lime expansion [32]. Partial cement replacement with a pozzolan such as FA will eliminate the negative effects of Ca(OH)² since the pozzolanic reaction between Ca(OH)² and reactive SiO², decreases the amount of Ca(OH)² in concrete [33]. According to Figure 7 the flexural strength of the LFC contain 15% and 30% FA are higher than that of controlled concrete. From results, 15% replacement of cement by FA improved flexural strength of all series about 3-18%. For each density, the percentage of improvement was permanently the same in all temperature degrees except for LFC with 600 kg/m³ density that improvement was more significant at higher temperature.

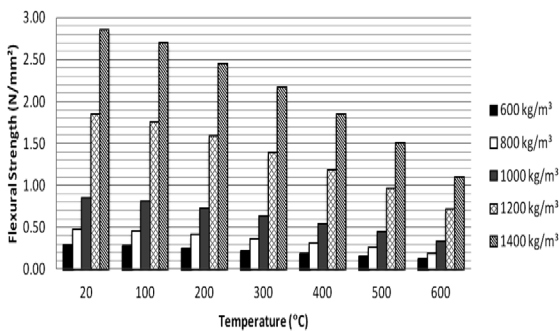
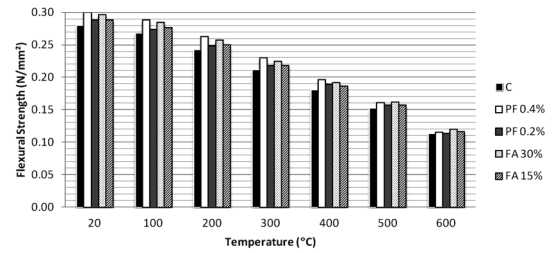
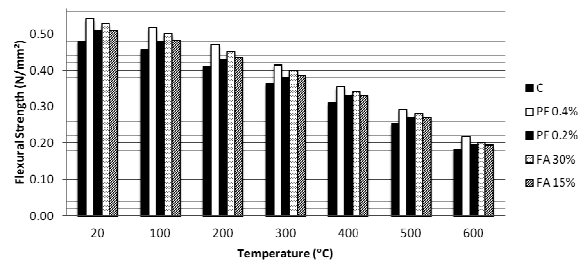


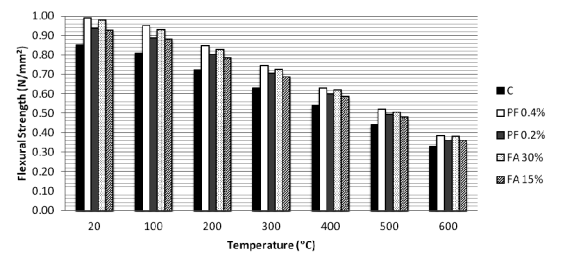
Figure 6. Flexural tensile strength of control LFC with different densities



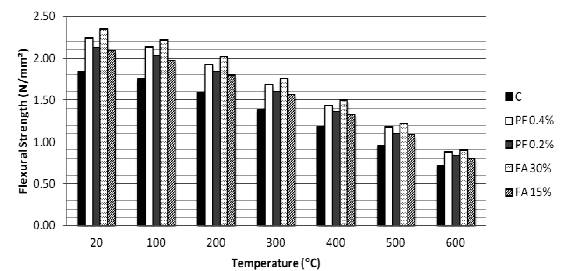
(a) 600 kg/m³



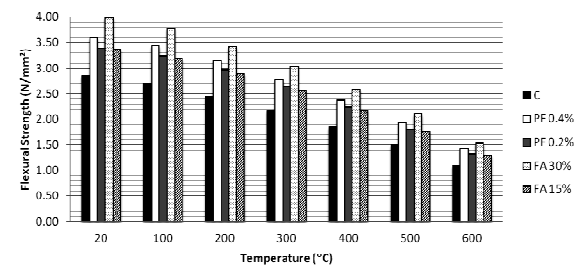
(b) 800 kg/m³



(c) 1000 kg/m³



(d) 1200 kg/m³



(e) 1400 kg/m³

Figure 7. The high temperature flexural strength of LFC made by different compositions

For LFC with 800 kg/m³ density, 15% replacement of cement with FA, increased the flexural strength by about 6% at each applied temperatures followed by 9%, 13% and 18% improvement of the flexural strength of LFC with 1000, 1200 and 1400 kg/m³ densities respectively. Generally, for both percentages, replacement of cement with FA was more effective for LFC with higher density. At each examined temperature, 30% cement replacement with FA increased the flexural strength of LFC with 800, 1000, 1200 and 1400 kg/m³ densities by about 10%, 15%, 27% and 40% respectively.

FA increases the resistance of concrete against high temperature due to the formation of tobermorite that is a product of lime and FA at high pressure and temperature which is about two to three times stronger than the CSH gel [34, 35]. Optimum level of FA was 30% which improved the flexural strength of LFC by 4-40% since the higher FA contents led to more evenly distributed cracks. Calcium hydroxide is reduced in cement paste, due to pozzolanic reaction and reduced cracking in LFC at high temperature

3. 3. 2. Polypropylene Fiber (PF) The bending strength allows a better access to the characteristic of fiber in LFC under high temperature since the main reason of adding fibers into concrete is to improve the ability of concrete to absorb energy and to sustain loads after the first crack through acting like a bridge across induced cracks [36].

From Figure 7 flexural strength of LFC increased about 4-22% and 7-30% by adding 0.2% and 0.4% PF respectively compared to that of controlled concrete. Improvement value depends on several factors such as fiber content, concrete density and the applied temperature. Level of improvement increased with density; adding PF to LFC with higher density was more effective e.g. 0.4% PF increased the flexural strength of 600 kg/m³ density by about 10% at 600 °C while the improvement value for 1400 kg/m³ density was 30% higher than its original value at the same temperature. Generally, at each applied temperature, flexural strength of higher density LFC was increased significantly by adding PF compared to LFC with lower density. In addition, improvement level at different temperatures was different; for all densities adding PF was most effective at 600 °C and the least value of improvement can be seen at the ambient temperature. PF melt at nearly 160–170 °C and produce expansion channels. Melting of the fibers creates additional porosity and small channels that reduce the internal vapour pressure in the concrete and thus, decrease the possibility of spalling [14]. From the results, the optimum level of adding PF to LFC was 0.4%, which considerably improved the flexural strength of composite and reduced spalling at the high temperature

by decreasing the shrinkage cracks.

4. FLEXURAL STRENGTH PREDICTION

There are few models recommended to predict the tensile strength of normal concrete at high temperature. Othuman Mydin and Wang [10] examined following models on LFC at different temperatures and concluded that the model proposed by Li and Gao [37] were a near perfect match with test results since the model of Anderberg and Thelandersson [38] provided the upper bound for f_{cr} . The intention of this section is to examine the applicability of these models to flexural strength of LFC incorporating different percentages of FA and PF at high temperature.

The Anderberg and Thelandersson [38] model include three equations for concrete exposed to temperature in a range of 20°C -1000°C degrees:

$$f_{crT} = f_{cr}(-000526T + 1.01052) \quad 20^{\circ}\text{C} < T < 400^{\circ}\text{C} \quad (1)$$

$$f_{crT} = f_{cr}(-0025T + 1.8) \quad 400^{\circ}\text{C} < T < 600^{\circ}\text{C} \quad (2)$$

$$f_{crT} = f_{cr}(-00005T + 0.6) \quad 600^{\circ}\text{C} < T < 1000^{\circ}\text{C} \quad (3)$$

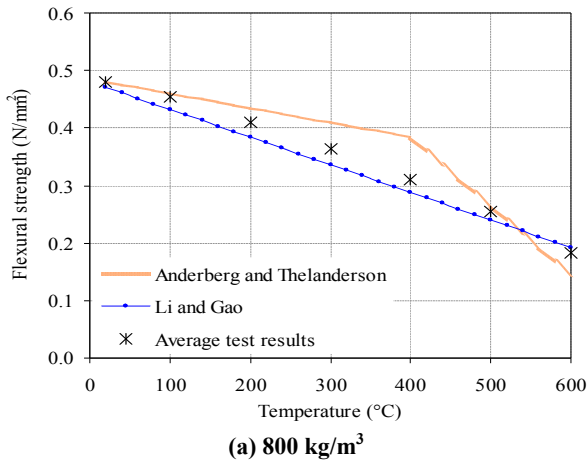
where f_{crT} and f_{cr} are the tensile strength of concrete at high temperature and ambient temperature correspondingly and T is temperature in °C. Li and Guo [37] also recommended an equation for prediction of tensile strength of a high temperature exposed concrete:

$$f_{crT} = f_{cr}(1-001.T + 0.6) \quad 20^{\circ}\text{C} < T < 1000^{\circ}\text{C} \quad (4)$$

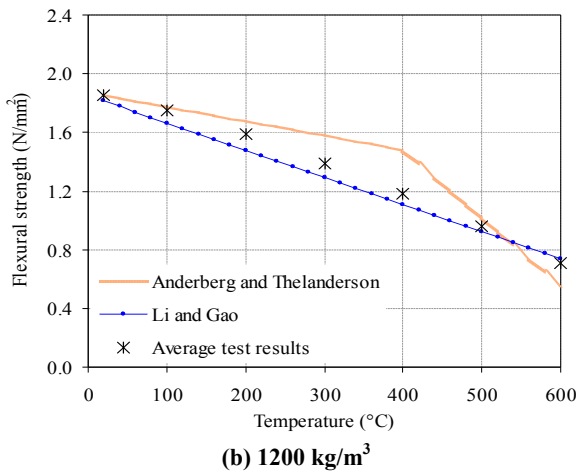
Figure 8 shows a comparison between the predicted strength and the average test results for LFC with and without additives. From comparison following data are obtained. The predicted flexural tensile strength values by Li and Guo model are 2-4% lower than those of the experimental results at ambient temperature. At 100, 200, 300 and 400 °C predicted values are 5-10%, and at 500 and 600 °C 0-7% lower than those of the experimental results. Using Anderberg and Thelandersson [38] prediction model, the predicted flexural tensile strength values are equal to experimental results up to 100 °C. At 200, 300, 400 and 500 °C the predicted values are 2-7, 9-14, 18-21 and 0-7% higher than the experimental results respectively. However, at 600 °C, the predicted values are 20-30% lower than the experimental results.

Figure 9 shows the comparison between the predicted flexural strengths using different models and the average test results for LFC incorporating 0.2% PF. Whereas, Figure 10 illustrates the comparison between the predicted flexural strength using different models and the average test results for LFC incorporating 30% FA. It can be clearly seen from these figures that the most reliable model for predicting flexural strength of

LFC incorporating FA and PF and also LFC made by ordinary Portland Cement CEM1 at high temperature is Li and Guo prediction model.

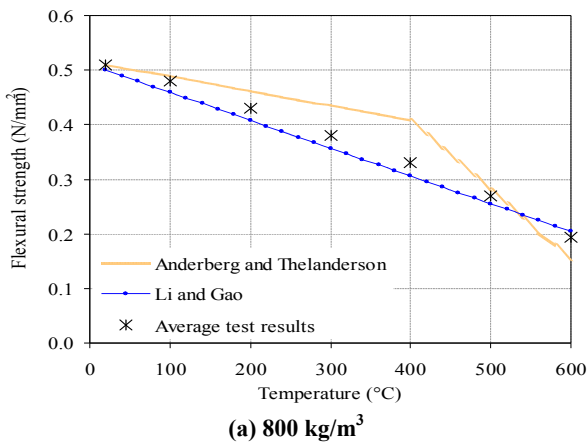


(a) 800 kg/m³

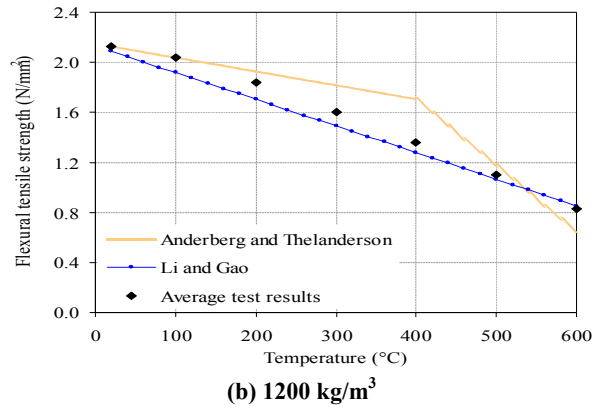


(b) 1200 kg/m³

Figure 8. Comparison between the predicted strength using different models and the average test results for controlled LFC

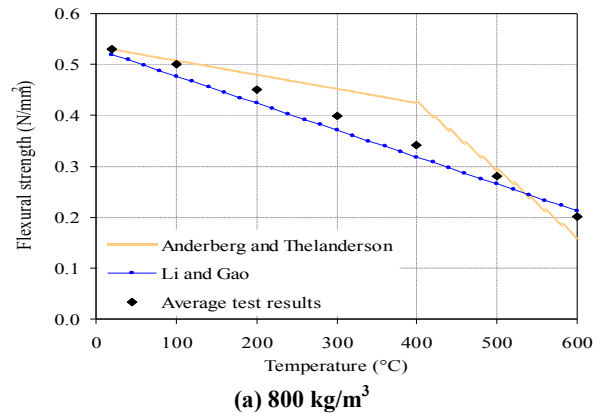


(a) 800 kg/m³

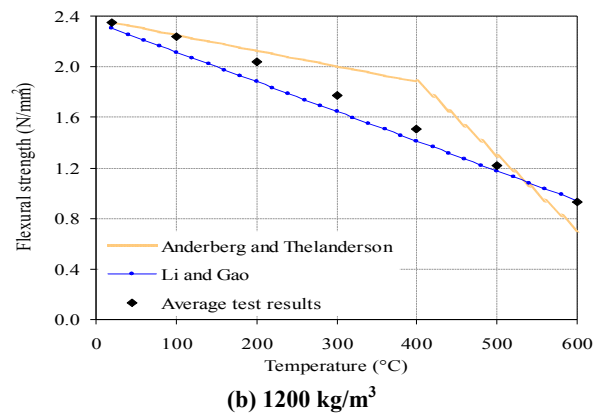


(b) 1200 kg/m³

Figure 9. Comparison between the predicted strength using different models and the average test results for LFC incorporate 0.2% PF



(a) 800 kg/m³



(b) 1200 kg/m³

Figure 10. Comparison between the predicted flexural strength using different models and the average test results for LFC incorporate 30% FA

5. CONCLUSION

This study investigated the flexural strength of LFC containing additives at high temperatures. Several

conclusions can be drawn from the experimental and comparative results as follow:-

1. LFC flexural strength decreases with temperature. Early heating of LFC causes delayed ettringite formation at temperatures above 65°C, but physical and chemical changes occurs between 93 and 200°C when evaporation of the free moisture contained in the concrete mass occurs.
2. The flexural strength of the LFC contain 15% and 30% FA are higher than the controlled concrete. Generally, for both percentages, cement replacement by FA is more effective for LFC with higher density. Optimum value of cement replacement with FA is 30% of cement mass which improves the flexural strength of LFC by 4-40%.
4. Flexural strength of LFC increases about 7-30% and 4-22% by adding 0.4% and 0.2% PF respectively. Improvement percentage increases with density. Generally, at each applied temperatures, flexural strength of higher density LFC is more enhanced by adding PF compared to LFC with lower density.
5. The most reliable model for predicting flexural strength of LFC incorporating FA and PF and also LFC made by ordinary Portland Cement CEM1 at high temperatures is that suggested by Li and Guo.

6. ACKNOWLEDGEMENT

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Influence of High Temperatures on Flexural Strength of Foamed Concrete Containing Fly Ash and Polypropylene Fiber

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در این تحقیق، استحکام خمشی بتن سبک فوم (LFC) که شامل خاکستر بادی (FA) و فایبر پروپیلن (PF) می باشد تحت درجه حرارت بالا به صورت تجربی و آماری بررسی شده است. متغیرهای این پژوهش عبارتند از: دما (در محدوده ۲۰ تا ۶۰۰ درجه سانتی گراد)، چگالی های در نظر گرفته شده برای بتن فوم شامل ۶۰۰، ۸۰۰، ۱۰۰۰، ۱۲۰۰ و ۱۴۰۰ کیلوگرم بر متر مکعب، و همچنین نوع و درصد مواد افزودنی. به طور کلی پنج ترکیب متفاوت از LFC مورد بررسی قرار گرفتند. دو ترکیب با جایگزین کردن FA با ۱۵ و ۳۰ درصد از جرم سیمان ساخته شدند. در دو ترکیب دیگر، به اندازه ۰.۲ و ۰.۴ درصد حجم سیمان PF اضافه شد. ساخت یک ترکیب هم به عنوان کنترل کننده و بدون مواد افزودنی صورت گرفت. سپس، استحکام خمشی این ترکیب ها در دماهای بالا بررسی شد. کاهش مقاومت خمشی LFC با افزایش دما عمدتاً به دلیل تشکیل ترک های مویی در دماهای بالاتر از ۹۳ °C می باشد زیرا استحکام خمشی به طور قابل ملاحظه ای با افزایش ترک ها رابطه معکوس دارد، به طوری که در این ترکیب ها در دمای ۶۰۰ °C کاهش شدید مقاومت ملاحظه شد و استحکام خمشی تنها به حدود ۴۰ درصد از مقدار اولیه خود رسید. در تمامی دماهای اعمال شده، استحکام خمشی LFC با چگالی بالاتر، بیشتر بود. در دماهای بالا، استحکام خمشی LFC با مشارکت FA و PF افزایش پیدا کرد و درصد این افزایش برای ترکیب هایی با چگالی بالاتر و مشمولیت بیشتر FA و PF چشمگیرتر بود. علاوه بر این، کاربرد برخی از مدل های پیشنهاد شده برای بتن معمولی، برای پیش بینی مقاومت خمشی فوم بتنی که شامل درصد های متفاوتی از FA و PF است و در معرض درجه حرارت بالا قرار دارد، بررسی شده و مطمئن ترین مدل برای تحقیقات آینده پیشنهاد شده است.

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