Prediction of Elevated Temperature Flexural Strength of Lightweight Foamed Concrete Strengthened with Polypropylene Fibre and Fly Ash

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Abstract

This paper focuses on an experimental investigation and statistical analysis of elevated temperature flexural strengths of lightweight foamed concrete (LFC) strengthened with polypropylene fiber (PF) and fly ash (FA) up to 600°C. Five mixes of LFC with 600, 800, 1000, 1200 and 1400 kg/m³ densities were made and tested in current exploration. Two mixes were casted by substituting 15% and 30% of cement content with FA and in other two series; PF was added to LFC mix, correspondingly by 0.2% and 0.4% of binder volume, one controlled mixture without additives was also fabricated. From the experimental results, it can be concluded that the lessening of LFC flexural strength exposed to elevated temperature may be mainly due to the formation of micro cracks at temperature exceeding 93°C since the flexural strength is unfavourably influenced by formation of cracks so that a rigorous strength loss was experiential at 600°C and the flexural strength was only about 40% of its original value. In order to predict the flexural strength of LFC at high temperatures, some existing models applied for normal strength concrete have been considered. The most consistent model for predicting flexural strength of LFC strengthened with PF and FA and also LFC made by ordinary Portland Cement CEM1 at elevated temperature is Li and Guo prediction model.

Keywords: foamed concrete, flexural strength, bending strength, elevated temperature, polypropylene fiber, fly ash

1. Introduction

Lightweight foamed concrete (LFC) is an immense preponderance of concrete containing no large aggregates, only fine sand and with exceptionally light weight materials containing cement, water and foam. LFC is categorized as lightweight concrete that been formed by cement paste in which air-voids are entrapped in the mortar by a suitable foaming agent. To date, LFC has been utilized predominantly as a filler material in construction and civil engineering works. However, its good thermal and acoustic performance designates its strong prospective as a material in building construction. The development of hydrolyzed protein based foaming agents and specialized foam generating equipment has improved the stability of the foam, making it possible to manufacture LFC for structural applications.

The degradation mechanisms of LFC at elevated temperatures comprise chemical degradation and mechanical worsening. 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 (Li et al., 2004). Existence of cracks caused by high temperature leads to reduction of LFC strength. However, the cracking degree influences more importantly the flexural strength than the compressive strength since the flexural strength is more sensitive to cracks caused by high temperatures to concrete. Othuman Mydin and Wang (2012) conducted a research on mechanical properties of LFC subjected to elevated temperatures. And they found that the flexural strength of LFC decreased primarily past 90°C. It was concluded that micro cracking is the main mechanism causes degradation, which occurs as the free water and chemically bound water evaporates from the porous body.

Song et al (2005) 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. For decades, fibers have been extensively used to improve ductility of concrete. According to Sing et al. (2004) 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 fiber which can also improve the residual characteristic of concrete exposed to elevated temperatures. Several studies have shown that the thermal stability of concrete is improved by incorporating polypropylene fibers (PF) into the mix (Kalifa et al., 2001). PFs have been used to considerably reduce the amount of spalling effect and cracking whilst enhance the residual strength. The micro PFs decrease the shrinkage micro cracks before heating and reduce the spalling at the high temperature. However, minimal or detrimental effects of the PFs on the residual behavior of the heated concrete were also observed.

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 was proved by several researches. At elevated temperature, the compressive and splitting tensile strength loss in concrete contains 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. The increase in strength can be caused by the high strength ceramic bonds that created due to thermo-chemical reactions at elevated temperatures. In addition, FA reduces the surface cracking of concrete both at elevated temperatures and after post-cooling in air or water. There is a lack of information on thermal properties of LFC contain additives at elevated temperature since the most of researches were carried out on LFC properties at ambient temperature.

Hence, the main purpose of this research is to examine the effect of high temperature on the flexural strength of LFC strengthened with PF and FA. Five different mixes will be made 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, respectively by 0.2% and 0.4% of binder volume. In mix design a constant water-cement ratio of 0.5 and cement-sand ratio of 2:1 will be considered for all series. Afterwards, 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 were made of cement, water, filler and a liquid chemical diluted with water and aerated to form the LFC samples for this research 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.

Two types of furnaces were utilized in sequence to heat the samples including low temperature electric furnace and high temperature electric furnace with a maximum operating temperature of 450 and 1000°C respectively. 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 1** show an electric furnace used to heat LFC samples.

Figure 1. Electric furnace.

For flexural strength test, rectangular parallelepipeds of height (h) 25 mm, width (w) 125 mm and length L (l) 350 mm dimensions sample 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 2. The maximum stress and strain were calculated on the incremental load applied for the evaluation of bending strength.

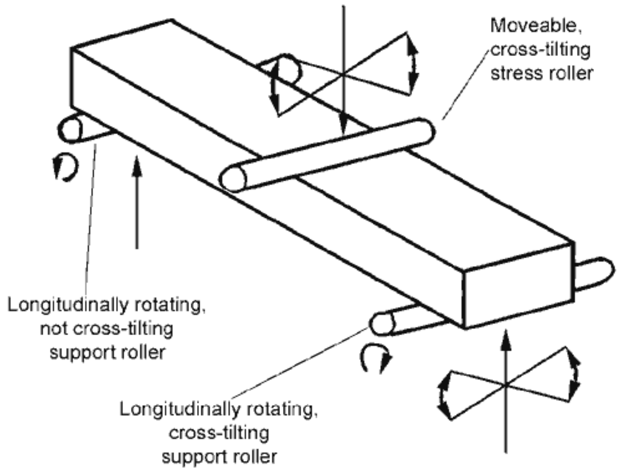

Figure 2. Simply supported specimen subjected to a concentrated load at the mid span.

3. Experimental Results and Discussion

3.1 Flexural Strength-Temperature Relationship

Figure 3 demonstrates the flexural strength of control LFC at different temperatures. It can be clearly seen from Figure 3 that the LFC flexural strength decreased with temperature for all densities considered for this study. Physical and chemical changes and slight volume changes take place between 93 and 200 °C when evaporation of the free moisture. Thus at 200 °C flexural strength reduced to 85% of its original value for all series. At a temperature of 200 to 300 °C, dehydration caused decomposition of the C-S-H and sulfoaluminate phases and surface hairline cracks begin to form. Therefore, 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. At 600°C flexural strength was only about 40% of the original value for all densities

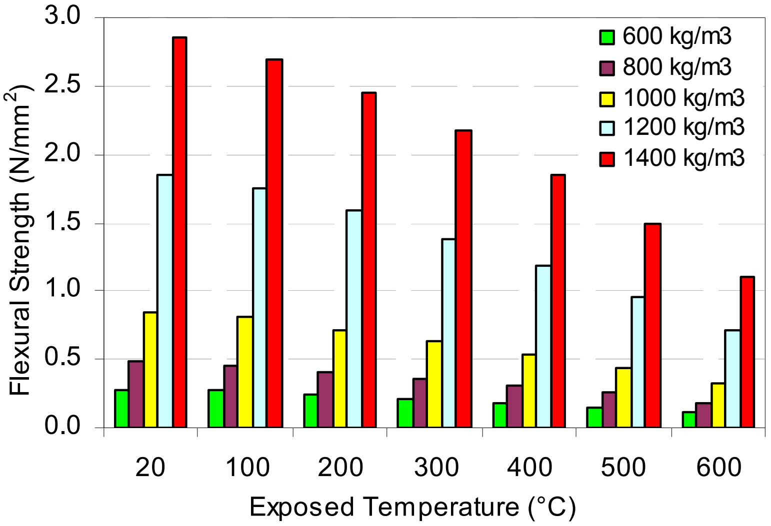

Figure 3. Flexural strength of control LFC exposed to different temperatures.

3.2 Flexural Strength-Density Relationship

Flexural strength of control LFC with different densities at each applied temperature ranging from 20 to 600°C is presented in Figure 4. It can be seen that flexural strength of LFC with higher density achieved a higher value at each predetermined temperature. As far as LFC is concern, its density is controlled by the air during the 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 display more open microstructure in comparison with higher density mixes of the same mix constituents and they enclose 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 to binder ratio, the lower density LFC with greater air contents will have a lower flexural strength.

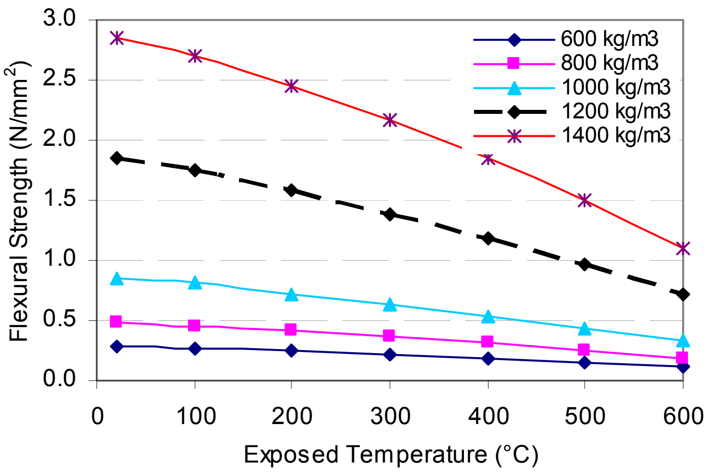

Figure 4. Flexural tensile strength of control LFC with different densities

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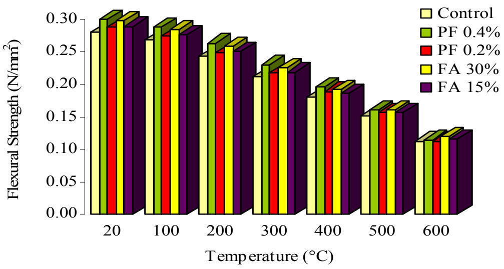
3.3 Flexural Strength-Additive Relationship

It can be seen from Figure 5 that flexural strength of LFC increased about 4-22% and 7-30% by adding 0.2% and 0.4% PF correspondingly compared to that of control LFC. Enhancement in flexural strength depends on numerous factors such as the fiber content, LFC density and the temperature level. By adding PF to LFC with higher density was more effective e.g. 0.4% PF increased the flexural strength of 600 kg/m^3 density by about 10% at 600°C while the improvement value for 1400 kg/m^3 density was 30% higher than its original value at the same temperature. Commonly, at each temperature exposure, flexural strength of higher density LFC was increased significantly by adding PF compared to LFC with lower density. In addition, improvement level at different temperature was different; for all densities adding PF was most efficient 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. The optimum level of adding PF to LFC was 0.4% which significantly improved the flexural strength of composite and reduced spalling effect at the elevated temperature by decreasing the shrinkage cracks.

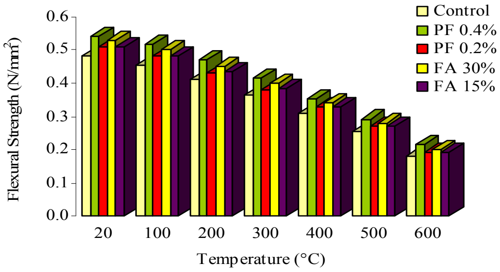
On the other hand, the flexural strength of the LFC contain 15% and 30% FA are higher than that of controlled concrete (refer Figure 5). From figure 5, by replacing 15% of cement content by FA improved flexural strength of all series about 3-18%. For each density, the percentage of improvement was permanently the same in all temperature degrees except for LFC with 600 kg/m^3 density that improvement was more significant at higher temperature.

For LFC with 800 kg/m^3 density, 15% replacement of cement with FA, increased the flexural strength values 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/m^3 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.

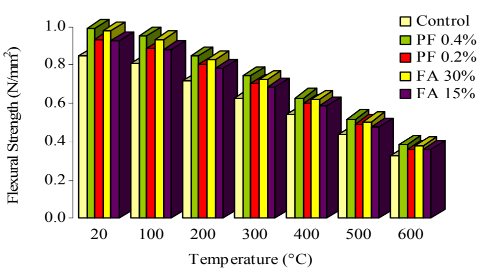
FA increases the resistance of concrete against high temperature due to the formation of tobermorite that is a product of lime and FA at high pressure and temperature which is about two to three times stronger than the CSH gel (Nasser and Marzouk, 1979). Optimum level of FA was 30% which improved the flexural strength of LFC by 4-40% since the higher FA contents led to more uniformly distributed cracks.



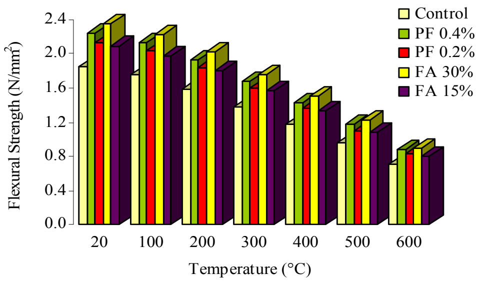
(a): 600kg/m^3 density



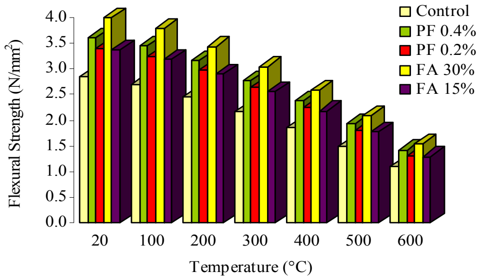
(b): 800kg/m^3 density



(c): 1000kg/m^3 density



(d): 1200kg/m^3 density



(e): 1400kg/m^3 density

Figure 5. Flexural strength of LFC made by different compositions at different temperatures

4. Models for Predicting Flexural Strength of Concrete at Elevated Temperature

Successful prediction of LFC properties results in a great time and cost savings to the concrete industry. However, despite increasingly interest in using LFC, there are very few available models for predicting properties of high temperature exposed LFC. Some models are suggested to predict the tensile strength of normal concrete at elevated temperature. Othuman Mydin and Wang (2012) examined following models (Eq. (1,2,3)) on LFC at different temperatures and concluded that the model proposed by Li and Gao (1993) were a near perfect match with test results since the model of Anderberg and Thelandersson (1976) provided the upper bound for f_{ct} and the values achieved by Eurocode 2 (2004) model did not fit well with experimental results. The aim of this section is to examine the applicability of these models to flexural strength of LFC incorporating different percentages of FA and PF at elevated temperature.

The Anderberg and Thelandersson (1976) model include three equations for concrete exposed to temperature in a range of 20-1000 degrees:

$f_{cr}T = f_{cr}$ (-000526T + 1.01052) 20°C<T<400°C (1a)

$f_{cr}T = f_{cr}$ (-0025T + 1.8) 400°C < T < 600°C (1b)

$f_{cr}T = f_{cr}$ (-00005T + 0.6) 600 °C < T < 1000 °C (1c)

where $f_{cr}T$ and f_{cr} are the tensile strength of concrete at elevated temperature and ambient temperature correspondingly and T is temperature in °C.

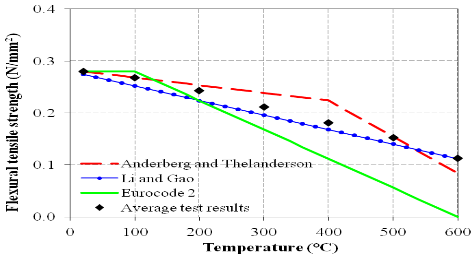
Two followings equations are prediction models suggested by Eurocode 2 (2004):

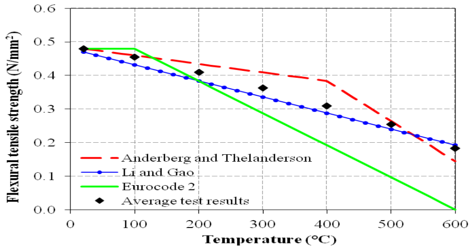
$f_{cr}T = f_{cr}$ 20°C < T < 100°C (2a)

$f_{cr}T = f_{cr}$ (-0.002T + 1.2 100°C<T<600°C (2b)

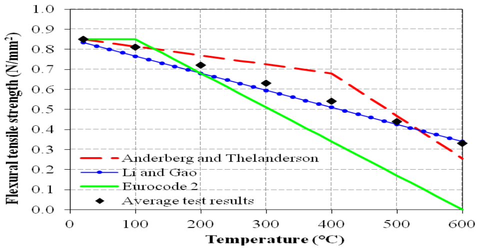
Li and Guo (1993) also recommended an equation for prediction of tensile strength of a high temperature exposed concrete:

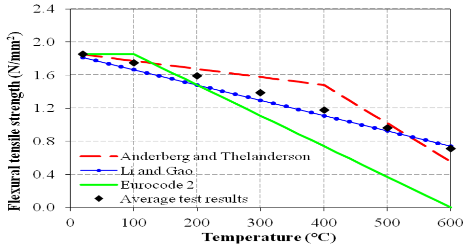
$f_{cr}T = f_{cr}$ (1-001 .T + 0.6) 20°C<T<1000°C (3)



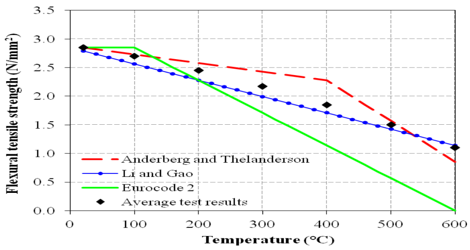


(a) 600 kg/m^3 (b) 800 kg/m^3



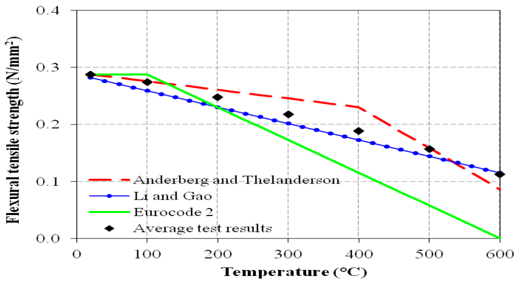


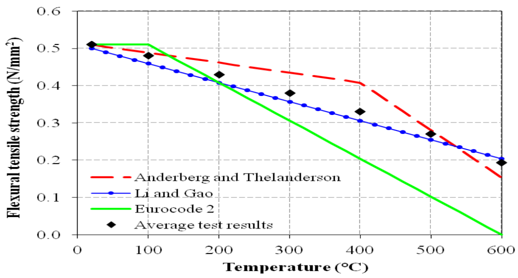
(c) 1000 kg/m^3 (d) 1200 kg/m^3



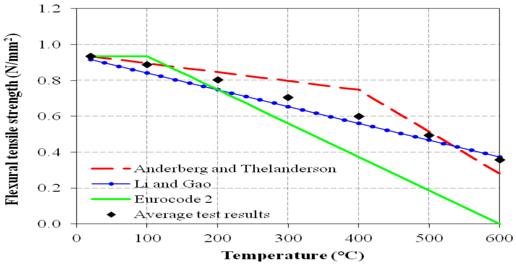
(e) 1400 kg/m^3

Figure 6. Predicted flexural strength using different models and the average test results for control LFC

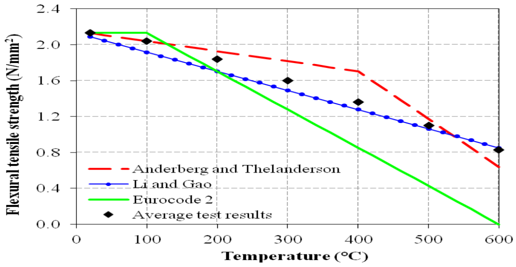




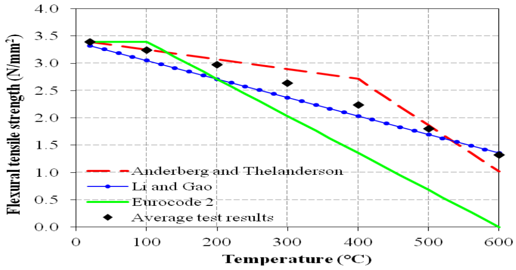
(a) 600 kg/m^3 (b) 800 kg/m^3



(c) 1000 kg/m^3



(d) 1200 kg/m^3



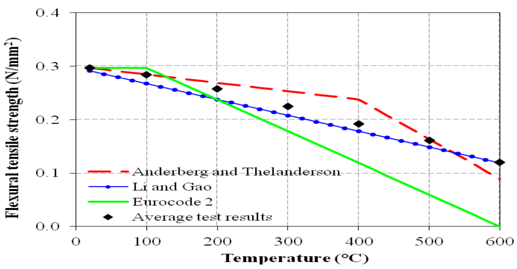
(e) 1400 kg/m^3

Figure 7. Predicted flexural strength using different models and the average test results for LFC incorporate 0.2% PF

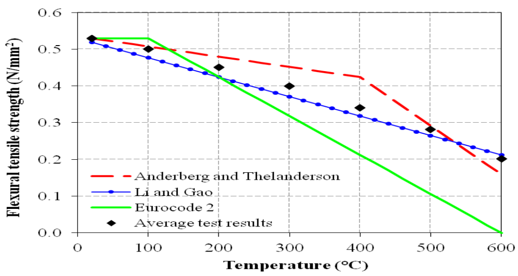
Figure 6 presents a comparison between the predicted flexural strength using mentioned three models and the average test results for LFC with and without additives. From comparison following data are obtained. The predicted flexural tensile strength values by Li and Guo model are 2-4% lower of the experimental results at the ambient temperature. At 100, 200, 300 and 400 °C predicted values are 5-10% lower of the actual values and at 500 and 600°C the predicted values are 0-7% lower of the experimental results.

Using Anderberg and Thelandersson (1979) 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 experimental results respectively. However, at 600 °C, the predicted values are 20-30% lower than the experimental results.

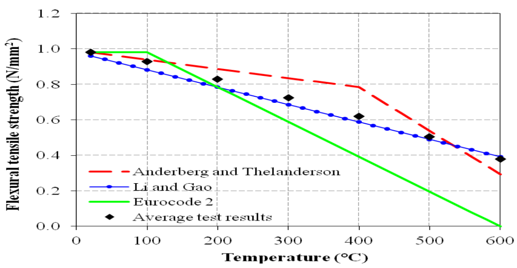
Predicted values by Eurocode 2 (2004) are equal to the experimental results at ambient temperature. At 200, 300, 400 and 500 °C, the predicted values are 5-10, 20, 36-40 and 60-63% lower than the experimental results respectively. Predicted value at 600 °C is equal to zero.



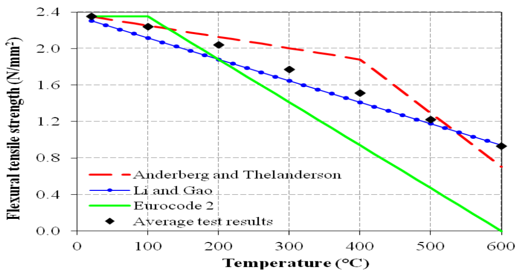
(a) 600 kg/m^3



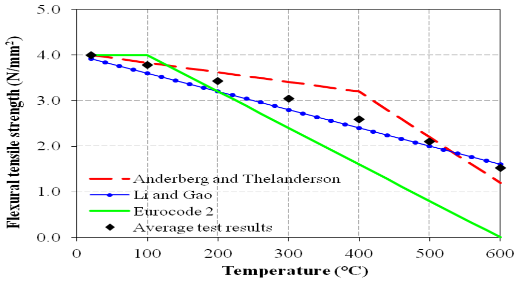
(b) 800 kg/m^3



(c) 1000 kg/m^3



(d) 1200 kg/m^3



(e) 1400 kg/m^3

Figure 8. Predicted flexural strength using different models and the average test results for LFC incorporate 30% FA

Figure 7 shows the comparison between the predicted flexural strength using different models and the average test results for LFC incorporate 0.2% PF. Whereas Figure 8 illustrates the comparison between the predicted flexural strength using different models and the average test results for LFC incorporate 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 elevated temperature is Li and Guo prediction model.

5. Conclusion

There are quite a few conclusions can be drawn from this study. LFC flexural strength decreases with temperature for all densities considered. At each predetermined temperature, flexural strength of LFC with higher density achieves a higher value since lower density LFC cement is more porous and contains more air void which eventually leads to reduction of hardened concrete density and strength. Flexural strength of the LFC contain 15% and 30% FA are higher than controlled concrete. Optimum value of cement replacement with FA is 30% of cement mass which improves the flexural strength of LFC by 4-40%. On the other hand, flexural strength of LFC increases about 7-30% and 4-22% by adding 0.4% and 0.2% PF correspondingly. Usually, at each applied temperatures, flexural strength of higher density LFC is more enhanced by adding PF compared to LFC with lower density. On top, enhancement percentage at different temperature is different; for all densities, adding PF is most effective at 600° C and the least value of improvement can be seen at the ambient temperature. From the results, the optimum level of adding PF to LFC is 0.4% which considerably improved the flexural strength of composite. Last but not least, the most reliable model for predicting flexural strength of LFC incorporating FA and PF and also LFC made by ordinary Portland Cement CEM1 at elevated temperature is Li and Guo prediction model.

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