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Original Article

Compressive and splitting tensile strength of autoclaved aerated concrete (AAC) containing perlite aggregate and polypropylene fiber subjected to high temperatures

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Abstract

This paper presents the results of an experimental study on the residual compressive and splitting tensile strength of autoclaved aerated concrete (AAC) containing perlite and polypropylene (PP) fiber subjected to high temperatures. Cylinder specimens were subjected to various temperature ranges of 100, 200, 400, 800, and 1,000°C. The mixtures were prepared with AAC cementitious materials containing perlite at 15%, 20%, and 30% sand replacement. The polypropylene fiber content of 0, 0.5%, 1%, 1.5%, and 2% by volume was also added to the mixture. The results showed that the unheated compressive and splitting tensile strength of AACs containing PP fiber were not significantly higher than those containing no PP fiber. Furthermore, the presence of PP fiber was not more effective for residual compressive strength than splitting tensile strength. The 30% perlite replacement of sand gave the highest strength. Based on the results, it can be concluded that addition of PP fiber did not significantly promote the residual strength of AAC specimens subjected to high temperatures.

Keywords: autoclaved aerated concrete, high temperature, polypropylene fiber

1. Introduction

Autoclaved aerated concrete (AAC) is composed of cementitious mortar surrounding disconnected air voids and microscopic air bubbles. The air bubbles are the results of gas formed within the mortar. High temperature and pressure steam help to create this autoclave cured concrete, which is rapidly formed and has dense microstructures. However, the dense microstructures of AAC cause a disadvantage where fire resistance is concerned. The absence of voids, which relieves the internal stress, creates a major problem. This problem can be solved by adding fibers to the mixtures (Aydin *et al.*, 2008). For decades, fibers have been extensively used to improve ductility, reduction of spalling and cracking, and to enhance residual strength of concrete (Han *et al.*, 2005; Noumowe, 2005). Singh *et al.* (1993) reported that fibers were increasingly used for reinforcement of cementitious matrix to enhance the toughness and energy-absorption capacity and to reduce the cracking sensitivity of the matrix. Song *et al.* (2005) found that crack control played a crucial role in performance life of concrete construction. Concerning the crack control, the incorporation of discrete fibers into vulnerable concrete was useful and effective. However, negative effects of perlite and polypropylene (PP) fiber on the residual performance of the heated concrete were also recognized (Chan, 2000).

Improving properties of construction materials with natural volcanic materials are becoming wide-spread and their use as construction materials can lead to low-cost and green construction. The use of alternative natural lightweight aggregates instead of processed artificial aggregates can significantly reduce cost of such construction materials. Perlite

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is an amorphous volcanic glass which contains 2-5% water (Mladenovic *et al.*, 2004), typically formed by the hydration of obsidian. It occurs naturally and has the property of greatly expanding when heated sufficiently. The result of steam forms bubbles within the softened rock to produce a frothy-like structure. The formation of bubbles allows perlite to expand up to 15-20 times of its original volume (Gunning, 1994). With such property, perlite has been used as a composite in construction materials such as brick, plaster, pipe, wall and floor block. However, few studies have been conducted on the effects of high temperature on residual compressive strength, fracture properties of the lightweight concrete and AAC related materials that are mixed with and without fibrous additives (Valore, 1954; Tanacan, 2005). Fire resistance of AAC is primarily affected by temperature, duration, and condition of the fire. The effects of high temperature are visible in the form of surface cracking and spalling (Ali *et al.*, 2004; Georgali and Tsakiridis, 2005). Surface color of specimens can also be noticed during the exposure of high temperatures (Yuzer *et al.*, 2004). The alternations produced from exposure temperatures are more obvious when specimens are heated surpasses temperature of 500°C. Mirza and Soroushian (2002) conducted an experiment on PP and steel fiber reinforcement on lightweight concrete. They found that both PP and steel fiber reinforcement had a possibility to increase the flexibility of lightweight concrete. Similarly, Sinica *et al.* (2000) found that introducing carbon fibers with filament, which were 5 mm 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 was increased by 24.5%. Bilodeau *et al.* (2004) conducted an experiment on polypropylene fibers for preventing the spalling of light weight concrete subjected to hydrocarbon fire. He found that the required amount of PP fiber was close to 3.5 kg of the 20 mm PP fibers per cubic meter of concrete in order to prevent the spalling of a low w/c lightweight concrete which was made with silica fume-blended cement, when subjected to hydrocarbon fire. The objective of this research was to increase the insight of the strength of AAC prepared with PP fiber reinforcement after exposure to elevated temperatures (up to 1,000°C). An assessment of the degree of deterioration of the AAC after exposure to high temperatures can extend the knowledge of whether AAC structures should be repaired or replaced. The effort may not project the best ray of solution to the problem, as its long-term effectiveness requires further investigation in the working field experience.

2. Experimental Details

2.1 Detail of design mix

The cementitious materials used in this study were Ordinary Portland cement (OPC) type I, which complied with BS 12:1991 and ASTM C150-92. The AAC specimens were made by the manufacturer, which has been certified by the Thailand Industrial Standard (TIS) 1505–2541. The composition of AAC is shown in Table 1. The properties of polypropylene fiber are shown in Table 2. Table 3 shows the composition of perlite used. The perlite contained 70-75% silicon dioxide and 12-16% alumina. Other components were sodium oxide, potassium oxide, ferro oxide, manganese oxide, titan oxide, and sulfide.

2.2 Preparation and testing methods

All AAC specimens were made according to the Thailand Industrial Standard (TIS) 1505–2541. The AAC specimens tested in this experimental study were G2 grade. This was due to the dimensional size of the furnace. The only three 100 mm (diameter) x 200 mm (height) cylindrical specimens could be fitted in the electrical furnace at a time. Therefore, the strength of AAC specimens was lower than the commer-

Table 1. Composition of autoclaved aerated concrete (AAC).

Composition (%)	Limestone	Cement	Sand	Perlite
SiO_2	-	21.02	85	71.02
Al_2O_3	0.5	5.21	6.1	16.09
Fe_2O_3	0.5	3.17	1.2	7.01
CaO	80	65.46	0.36	0.58
MgO	1	3.14	0.85	0.41
Na_2O	0.2	0.14	1	0.90
K_2O	0.42	0.83	1	5.59

Table 2. Properties of polypropylene fiber.

Properties	Data
Specific gravity	0.91
Tensile strength (MPa)	300-400
Modulus of Elasticity (MPa)	8000
Elongation at yield (%)	13
Water absorption	Nil
Range of melting temperature (°C)	160-175
Evaporation point (°C)	341
Burning temperature (°C)	460

Table 3. Composition of perlite.

Composition	Percent (by weight)
SiO_2	71.02
Al_2O_3	16.09
Fe_2O_3	7.01
CaO	0.58
$MgO_)$	0.41
Na_2O	0.90
K_2O	5.59
SiO_2	71.02

cial standard level (G4), where the results of compressive strength were from 150 mm (diameter) x 300 mm (height) specimens. The material properties were given in Table 1 involving high temperatures and pressure as the principle. The materials were mixed according to ASTM C192. Coarse materials were firstly added to the mixer, followed by approximately one-third of mixing water, and then the mixer was started. Fine cementious materials and water were added to the running mixer in a gradual manner. PP fiber was then added gradually to running mixer. The addition of PP fiber took approximately 2 min. Then, the mixer continued without fibers addition for 3 min. After 3 min, the final mixing took 2 min. The specimens were casted in cylindrical molds, 102 mm in diameter and 204 mm in height. In two layers, each layer being consolidated using a vibrating table. The AAC specimens were then kept in pressurized chamber at the pressure of 10–12 bars and the temperature of 180–190°C for 8 hours. The specimens were cut into standard sizes and required test amount by electric cutting device. The size accuracy was measured by vernier caliper instrument. The specimens were then placed in the oven at the temperature of 75°C for 24 hours. The cylindrical specimens were ready to test for temperature exposure in the electrical furnace. The exposure temperatures were set at 100, 200, 400, 800, and 1,000°C. In the furnace, each three cylinder specimen was heated at constant rate of 10°C/min from room temperature (25°C) to a targeted exposure temperature. After that, specimens were held at the targeted temperature for three hours before the furnace was turned off and the specimens were then allowed to cool down naturally to room temperature. During the heating period, moisture in the specimens was allowed to escape freely. Compressive strength tests were carried out in accordance with ASTM C 39. The splitting tensile strength tests were done according to ASTM C 496. Each data point reflects the three test results.

3. Test Results and Discussion

3.1 Compressive strength

For the unheated specimens, cylinders were tested. Results in Table 4 show that the compressive strength obtained from the cylinder specimens were in the range of 1.20-1.27 N/mm^2, while, the strength of unheated AAC specimens mixed with perlite was within the range of 2.82-4.62 N/mm^2 depending upon content of replacement. It was found that the compressive strength of specimens increased in accordance with the increased content of perlite. However, there was an exception for the case with no fiber, where the compressive strength decreased when the content of perlite increased. This can be attributed to the transition amount of cystalization of tobermorite (Israngkura Na Ayudhya *et al.*, 2008).

For the effect of PP fiber dosage, Figure 1 shows the variation in unheated compressive strength with PP fiber dosage. It can be seen from Table 4 that the PP fiber dosage increased from 0 to 0.5% by volume, the compressive strength also increased 1.26%. On the other hand, as the PP fiber dosage increased from 0.50 to 1.0, 1.5 and 2%, compressive strength decreased 1.6%, 1.5%, and 1.5%, respectively. This was due to the amount and orientation of disperse fiber, which obstructed the voids. The interfacial bond between the PP fiber and disconnected air voids in AAC were weak. Furthermore, PP was chemically inert and hydrophobic, thus the potential for chemical bonding was limited (Hannant, 1987). Additionally, it appeared that an optimum strength occured at 0.5% PP dosage. For heated specimens, the compressive strength decreased as exposure temperature increased above 100°C, regardless of the fiber content.

For the heated specimens, the specimens with perlite were subjected to compare their specimens residual strength under various temperatures. It was found from Figure 2 to 5 that residual compressive strength decreased when the exposure temperature and the amount of perlite replacement increased. This was a pozzolanic effect due to sand proportion when specimens were subjected to high temperatures. It was a ratio of perlite mass content to total aggregate (sand and perlite) mass content that reduced the loss in specimen strength. However, the effect of PP dosage on high temperature behavior of AAC specimens containing 0, 0.5, 1, 1.5, and 2% PP fiber were investigated. The experimental program was implemented at 400°C, 800°C, and 1,000°C. The compressive and splitting strength of specimens before and after high temperature exposures were presented in Table 4. An increase in PP dosage beyond 0.5% by its volume did not change the strength performance considerably. With the presence of PP fiber, the strength of AAC deteriorated when the exposure temperature was greater than 200°C. Below 200°C, the residual compressive strength did not change significantly, However, the residual strength of xposure temperature greater than 400°C specimens dropped drastically. This was due to vaporization of PP fiber when the exposure temperature was beyond fiber melting point (Jianzhuang, 2006). Furthermore, the degradation of PP fiber created voids inside of the AAC structure. The creation of these voids and an increasing PP fiber ratio, which lowered the density of AAC slightly due to PP fiber's relatively low density, decreased the density and increased the porosity of the specimens. The consequence was a decrease in strength (Poon *et al.*, 1999). Generally speaking, for AAC specimens with and without PP fiber, the residual compressive strength of AAC mixed with perlite was superior to that of AAC. Thus, it may be inferred that the lower the content of perite, the more likely it is to spall under high temperature. However, it was observed that the lower in strength of specimens containing perlite could be found despite the losses in strength.

Before the heated specimens were subjected to splitting tensile strength test, the appearance of the specimen surface was carefully observed. It was found that specimens did not spall when the exposure temperatures were lower than 400°C. However, above 400°C, small crack lines and spalls on the surface of the specimens were noticed. Figure 6 shows that obvious explosive spalling was found in the specimens

Table 4. Compressive and splitting strength test results.

Mix (% fiber)	Applied temperature (°C)	AAC		AAC mixed perlite					
				15% replacement		20% replacement		30% replacement	
		Compressive strength (N/mm^2)	Splitting strength (N/mm^2)	Compressive strength (N/mm^2)	Splitting strength (N/mm^2)	Compressive strength (N/mm^2)	Splitting strength (N/mm^2)	Compressive strength (N/mm^2)	Splitting strength (N/mm^2)
0	Unheated	1.26	0.82	4.14	2.40	4.12	2.39	4.05	2.43
	100	1.33	0.87	4.16	2.41	4.32	2.59	4.45	2.58
	200	1.33	0.86	3.92	2.35	4.13	2.39	4.17	2.42
	400	1.27	0.82	3.52	2.04	3.74	2.17	3.84	2.23
	800	0.20	0.13	0.15	0.09	0.14	0.08	0.20	0.12
	1,000	0.19	0.12	0.14	0.08	0.13	0.07	0.15	0.09
0.5	Unheated	1.27	0.81	4.23	2.54	4.42	2.56	4.62	2.68
	100	1.39	0.90	4.40	2.55	4.64	2.69	4.74	2.84
	200	1.36	0.87	4.16	2.41	4.48	2.60	4.38	2.54
	400	1.29	0.84	3.36	1.95	3.52	2.04	3.94	2.28
	800	0.22	0.14	0.17	0.10	0.13	0.07	0.14	0.08
	1,000	0.21	0.14	0.16	0.09	0.11	0.06	0.13	0.07
1.0	Unheated	1.25	0.81	3.86	2.24	3.98	2.39	4.17	2.42
	100	1.36	0.88	3.12	1.81	4.16	2.41	4.33	2.51
	200	1.34	0.87	2.88	1.73	3.76	2.18	4.18	2.42
	400	1.28	0.83	2.64	1.53	3.28	1.97	3.44	2.00
	800	0.21	0.13	0.14	0.08	0.14	0.08	0.14	0.08
	1,000	0.20	0.13	0.14	0.08	0.14	0.08	0.15	0.09
1.5	Unheated	1.23	0.79	3.31	1.99	3.70	2.15	3.82	2.21
	100	1.33	0.86	3.04	1.76	3.92	2.27	4.08	2.37
	200	1.32	0.85	2.56	1.48	3.36	1.95	3.60	2.16
	400	1.29	0.84	2.32	1.35	3.04	1.76	3.12	1.81
	800	0.21	0.13	0.14	0.08	0.15	0.09	0.16	0.09
	1,000	0.19	0.12	0.13	0.07	0.14	0.08	0.14	0.08
2	Unheated	1.20	0.78	2.82	1.64	3.47	2.01	3.30	1.98
	100	1.29	0.83	2.64	1.58	3.28	1.97	3.60	2.16
	200	1.29	0.84	2.24	1.30	3.04	1.76	3.28	1.90
	400	1.27	0.83	2.16	1.25	2.56	1.48	2.88	1.67
	800	0.19	0.13	0.15	0.09	0.15	0.09	0.15	0.09
	1,000	0.17	0.11	0.13	0.07	0.13	0.07	0.09	0.05

at elevated temperature of 800°C and 1,000°C. The variation of the colors under rising temperature can be recognized under three main categories (Jianzhuang, 2006). Below 200°C, the AAC specimens color did not change noticeably; the specimens remained white. When temperature was increased to 400°C, the specimens became a pale brownish color, while above 800°C the surface color of all AAC specimens turned into lighter brown. The change in surface color of AAC specimens can be attributed to the change in texture and composition, expansion and crystal destruction during a high temperature (Ali, 2002). In brief, PP fiber did not show an affect on the color change within a cross-section for specimens subjected to elevated temperatures ranging from 100°C to 1,000°C.

3.2 Splitting tensile strength

For unheated specimens, it was found from Table 4 that an average splitting strengths of AAC and AAC mixed with perlite at 15, 20, and 30% were 0.86, 2.16, 2.30, and 2.34 N/mm^2 respectively. The splitting tensile strength increased as the content of perlite increased. However, the perlite content did not result in a significant improvement in the splitting tensile strength for the specimens. Similar results

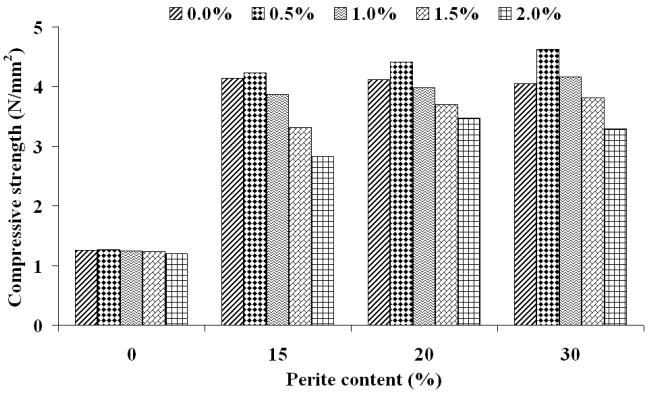

Figure 1. Unheated compressive strength of AAC mixed with PP fiber.

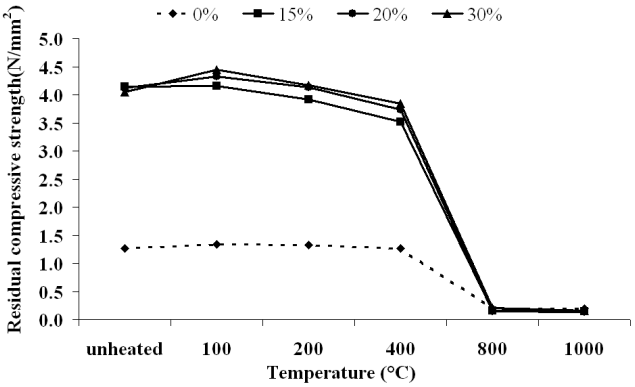

Figure 2. Residual compressive strength of AAC mixed 0% PP fiber.

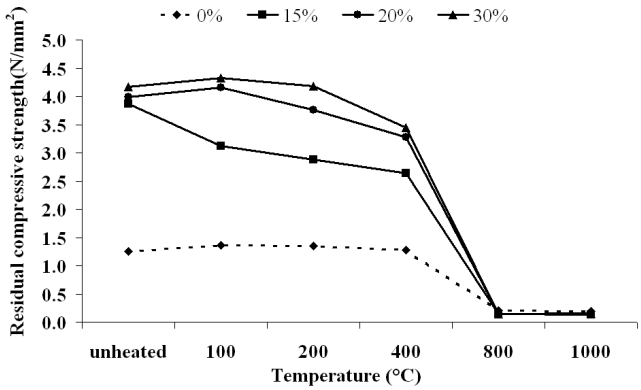

Figure 3. Residual compressive strength of AAC mixed 0.5% PP fiber.

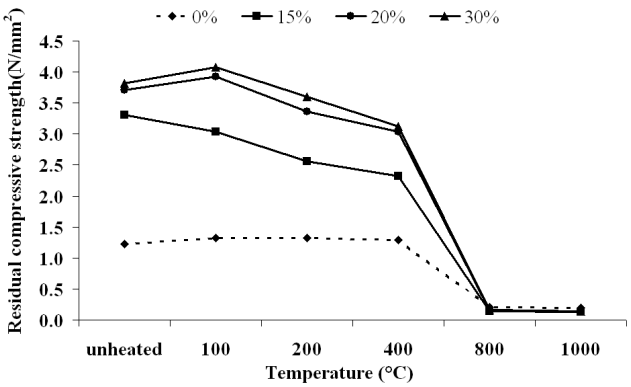

Figure 4. Residual compressive strength of AAC mixed 1.5% PP fiber.

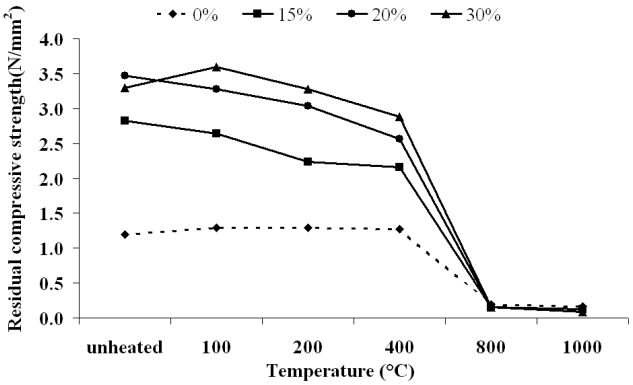

Figure 5. Residual compressive strength of AAC mixed 2.0% PP fiber.

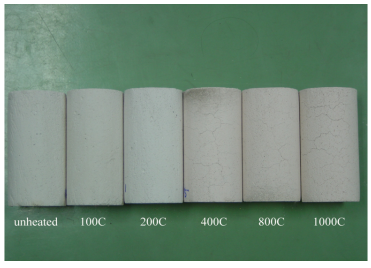

Figure 6. Heated AAC specimens.

have been reported by other researchers (Israngkura Na Ayudhya *et al.*, 2008).

Comparing with an increase in PP fiber dosage, Figure 7 clearly demonstrates that an increase in the amount of fiber dosage decreased the splitting tensile strength. The splitting tensile strength decreased significantly as the amount of PP dosage increased beyond 0.5% of its volume. Similar results were found by Qian (2000). However, at 0.5% fiber dosage, 30% sand replacement with perlite gave the highest unheated splitting tensile strength of 2.68 N/mm^2. It gained 230% strength compared to specimens containing no fiber and perlite.

For heated specimens, the variations of residual splitting strength of specimens after exposure to high temperature are shown in Figure 8 to 11. The specimens were subjected to a comparison between the content of perlite and temperature. It was found that the residual splitting strength decreased as the exposure temperature increased. More importantly, it was also found that the presence of perlite content did not show a significant improvement in the strength when specimens were subjected to high temperatures (800°C to 1,000°C).

It was found that an increasing fiber dosage increased the strength only when the PP fiber dosage was kept below 0.5% of its volume. However, the splitting tensile strength gained the highest strength when 0.5% of fiber was added and subjected to an exposure temperature of 100°C. The residual splitting strength was at 0.90 N/mm^2. It gained more 11% in strength than unheated specimens. However, a negative effect on strength performance was shown when the exposure temperature increased over 100°C. This negative effect of fiber dosage on residual strength was similar to the result of residual compressive strength. Furthermore, the

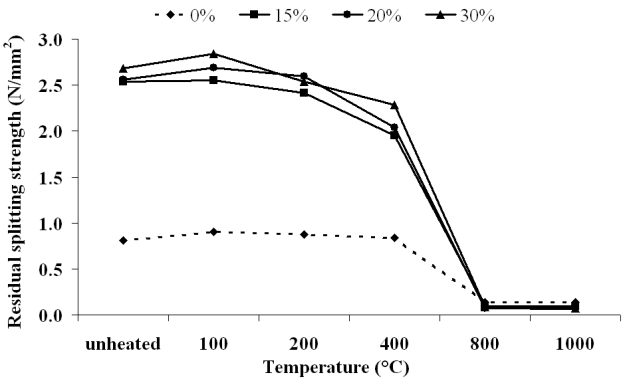

Figure 9. Residual splitting strength of AAC mixed with 0.5% PP fiber.

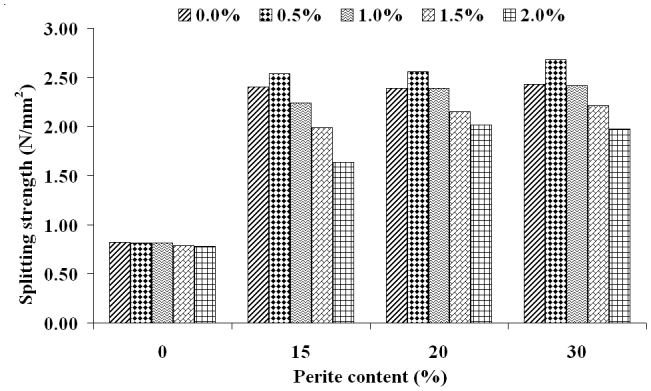

Figure 7. Unheated splitting strength of AAC mixed with PP fiber.

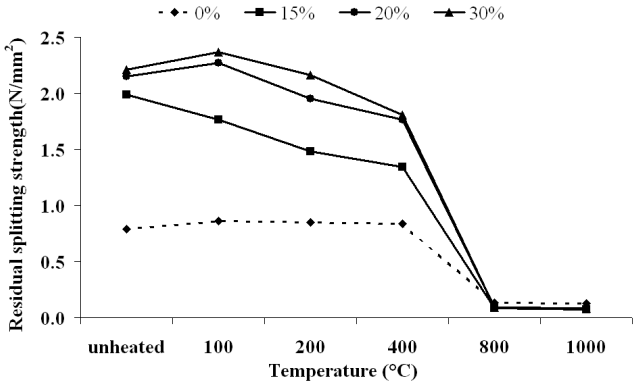

Figure 10. Residual splitting strength of AAC mixed with 1.5% PP fiber.

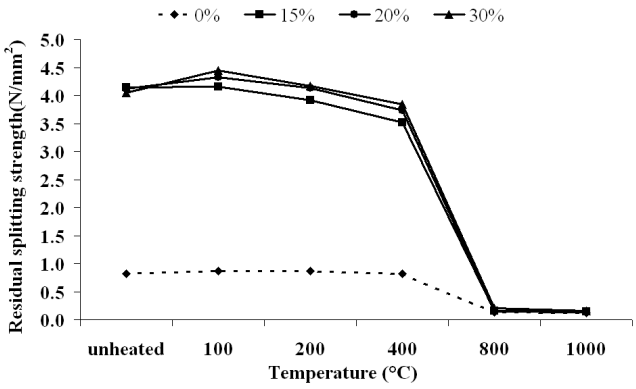

Figure 8. Residual splitting strength of AAC after heating.

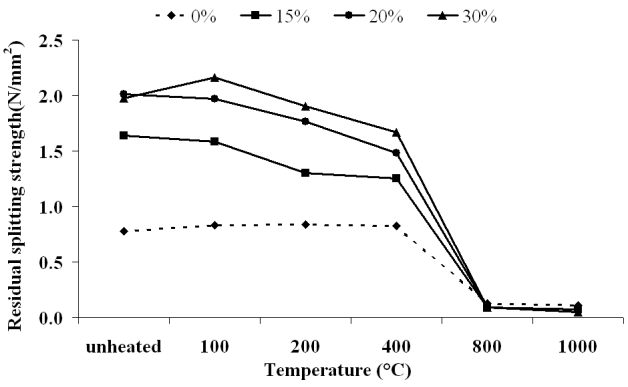

Figure 11. Residual splitting strength of AAC mixed with 2.0% PP fiber.

flocculation of fiber was sometimes noticed. It caused larger voids in AAC specimens, which reduced strength performance.

3.3 Correlations between residual strength of heated and unheated specimens

It was found that the ratio between compressive strength and splitting tensile strength on unheated and heated samples was in the range of 1.53 and 1.72, respectively, regardless of fiber content and the presence of perlite. The variation of ratio of compressive and splitting tensile strength is shown in Figure 12 to 15 for 0%, 15%, 20, and 30% perlite, respectively. The variation of the ratio of compressive and splitting tensile strength for non–perlite containing specimens was smaller than the variation of ratio of compressive and splitting tensile strength with mixed perlite. Furthermore, the variation of ratio of compressive and splitting tensile strength was greater when the exposure temperature above 800°C. This was due to the degradation mechanisms of AAC, which were mainly caused by a deprivation of the cement paste. When exposed to high temperatures, the chemical composition and physical structure of AAC changed significantly due to changes in the cement paste. However, there were fluctuations in ratio of compressive and splitting tensile strength at each exposure temperature. This might due to the flocculation of fiber during mixing time and the dispersion of perlite content after-casted. Nonetheless, the variation of ratio was within the range of ±1-2 N/mm^2. Furthermore, the content of perlite did not show a significant reduction in the variation of the ratio of compressive and splitting tensile strength. A 30% replacement sand with perlite resulted in an increase of the strength by 221% when compared with specimens containing no fiber.

4. Conclusions

The following conclusions can be drawn from the results of the experiment, which focused on the effect of the high temperatures on the strength of autoclaved aerated concrete with and without PP fiber.

1. It was found that high exposure temperatures had a significant effect on the strength performance. The strength of AAC was reduced when the exposure temperature increased. Especially, specimens that were subjected to temperature above 400°C, The strength rapidly declined. High

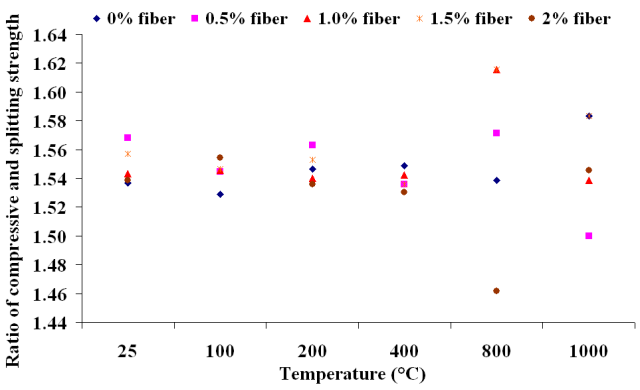

Figure 12. Ratio of compressive and splitting strength of AAC mixed with no perlite.

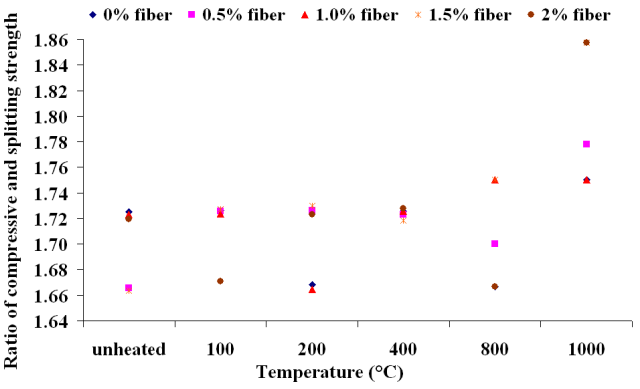

Figure 13. Ratio of compressive and splitting strength of AAC mixed with 15% perlite

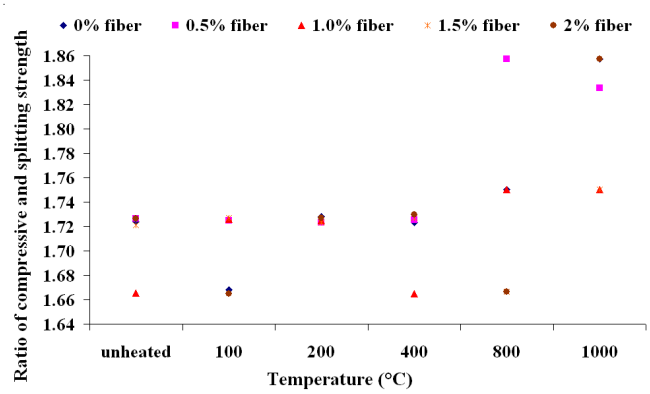

Figure 14. Ratio of compressive and splitting strength of AAC mixed with 20% perlite

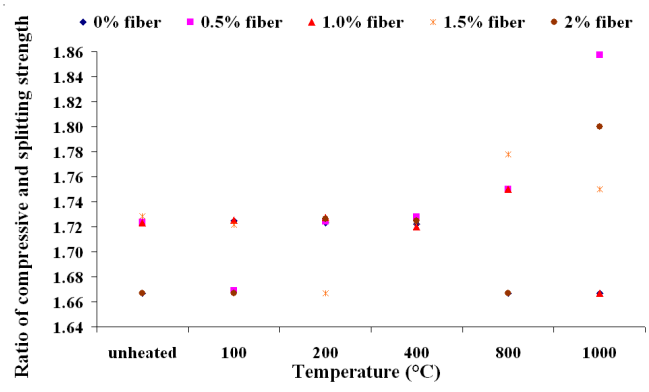

Figure 15. Ratio of compressive and splitting strength of AAC mixed with 30% perlite

exposure temperatures did have significantly effect the strength of the specimens when they were subjected to temperatures of 800°C and 1,000°C.

2. Introducing 0.5% by volume of PP fiber dosage in a mixing dose gave the highest strength of AAC. However, the effect of fiber dosage on strength decreased as the content of fiber was added above 0.5% by volume.

3. Replacement sand with perlite increased the unheated compressive and splitting tensile strength. 30% of replacement gave the highest strength results. However, there was an exception only for the case of no fiber, where the compressive strength decreased when the content of perlite increased. This can be attributed to the transition amount of crystallization of tobermorite. In addition, as perlite dosage increased, the quantity of mixing waster also increased considerably, which had a negative effect on strength performance.

4. The strength of material gradually increased as the exposure temperature went up to 100°C. Above 100°C the strength of material declined, regardless to the content of fiber and perlite. At 100°C, the heated strength of compressive and splitting was higher, approximately 5-9% of its unheated specimens, regardless the presence of fiber. The compressive and splitting tensile strength of specimens rapidly deteriorated at around 500-600% of its unheated specimens when the exposure temperature reached 1,000°C. This indicated that the primary mechanism causing strength degradation was microcracking, which occured as water expanded and evaporated from the pores of the structure.

5. Based on the test results, there was not enough evidence to support an increase of strength when perite and PP fiber was used together with AAC mixture.

6. The appearance of AAC specimens can be categorized into three categories. Below 200°C, the color remains white; Above 400°C, the color turn into pale brownish, and above 800°C, the color become lighter brown.

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