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Structural integrity of ferrocement panels exposed to fire

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Abstract

The structural fire integrity performance of a ferrocement jacket was experimentally determined based on its flexural characteristics and damage after exposure to fire. The main parameters investigated were the volume fraction of wire mesh and mortar cover. A sandwich-sample configuration was adopted to simulate the actual conditions of exposure to fire in which the maximum temperature of 1060 °C was reached within 3 h. Tests showed that a ferrocement jacket was a satisfactory fire protection material due to its post-fire strength compared with that of plain mortar. Although an increase in wire mesh content significantly improved the mechanical properties of ferrocement under normal conditions, after fire exposure the content of wire mesh was no longer significant and higher volume fractions of wire mesh resulted in in-plane cracking. Mortar covers had negligible influence on the mechanical properties of ferrocement jackets under both normal and after fire exposures. However more visible fire damage occurred in ferrocement with thinner mortar cover.

Keywords: Ferrocement; Fire protection; Fire-damage; Post-fire strength; Toughness; Crack patterns

1. Introduction

Fire remains one of the serious potential risks to most buildings and structures [1]. A weakening of structural materials when exposed to high temperatures has potential for building collapse. Therefore, the use of fire protection materials to reduce thermal damage of structural members is important and necessary. Many types of fire protection material were developed to protect structural members. The main classes of material used are cementitious, intumescent, fibrous and composite materials. Ferrocement is one of the cementitious composite materials, which is constructed of hydraulic cement mortar reinforced with closely spaced layers of continuous and relatively small sized wire mesh [2]. Since mortar is a good insulator and the reinforcing wire mesh can reduce surface spalling better than plain concrete, the application of ferrocement jacketing for other structural components like reinforced concrete, prestressed concrete, or steel can protect these structural members from fire. Moreover, the influence of the encasing effect of ferrocement jackets, which behave as additional confinement [3–5], enhance the fire performance of the composite elements.

The use of ferrocement as a fire protection material requires a full understanding of the effects of fire on this material. However, most previous research has focused on the individual properties of ferrocement material, i.e. concrete, mortar and steel, at high temperatures [6–12]. Several studies have been conducted on the effects of high temperatures on the mechanical behavior of discontinuous-fiber reinforced materials, i.e. steel and polypropylene fiber [13–16]. Nevertheless, there is still a lack of knowledge and experimental data on the behavior of ferrocement exposed to fire.

The purpose of this study is to investigate the structural integrity of a ferrocement jacket exposed to fire. Structural integrity is obtained experimentally from the flexural characteristics and damage to ferrocement panels after exposure to fire. The investigated parameters are the volume fraction of wire mesh and mortar cover. The ferrocement

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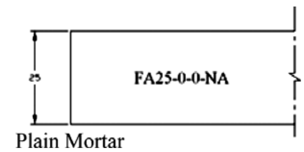
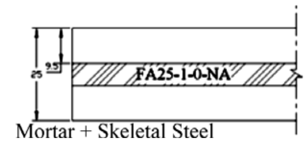
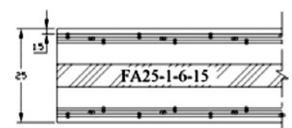
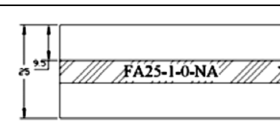
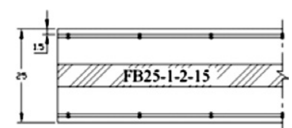
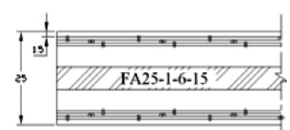
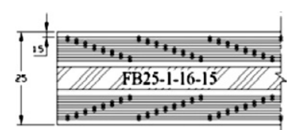
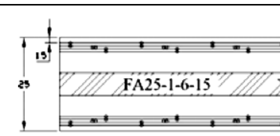
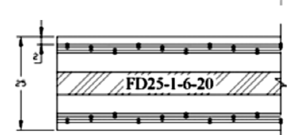
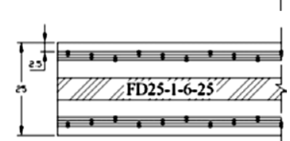
specimen had a dimension of 200 mm × 240 mm × 25 mm. Ordinary steel bar having a diameter of 6 mm was used as skeletal steel. Galvanized hexagonal steel wire meshes were used as mesh reinforcement. The mortar had a compressive strength of 57 MPa and was kept constant throughout. A sandwich-panel of ferrocement which consists of edge insulation was subjected to high temperature in order to simulate the heat transfer behavior of fire exposed ferrocement jackets. Type K thermocouples were used to record the temperatures. After being left to cool down in the furnace, the cracking, failure pattern, and damage to the ferrocement specimen's surface appearance

Table 1
Experimental program and details of test specimen

Series no.	Series code	Mortar overing (mm)	No. of wire mesh layers	Volume fraction (%)	Sectional geometry
A. Control specimen					
1	FA25-0-0-NA	NA	0	0	
2	FA25-1-0-NA	NA	0	0	
3	FA25-1-6-15	1.5	6	1.63	
B. To study the effect of volume fraction of wire mesh					
2	FA25-1-0-NA	NA	0	0	
4	FB25-1-2-15	1.5	2	0.54	
3	FA25-1-6-15	1.5	6	1.63	
5	FB25-1-16-15	1.5	16	4.36	
C. To study the effect of mortar cover					
3	FA25-1-6-15	1.5	6	1.63	
6	FC25-1-6-20	2.0	6	1.63	
7	FC25-1-6-25	2.5	6	1.63	

were evaluated by visual inspection. Subsequently, flexural strength tests [17] were conducted to investigate the mechanical properties and deterioration of ferrocement after exposure to fire.

2. Experimental program

This study investigated the effect of the volume fraction of wire mesh and mortar cover on post-fire mechanical properties of ferrocement. The experimental study was carried out in five steps: specimen preparation, preliminary observation, fire exposure, tests on physical and mechanical properties, and determination of the deterioration of ferrocement. Altogether seven series of ferrocement specimen were produced and divided into three groups, namely Group A, B and C in order to make a comparison with each parameter. Group A was conducted in order to observe the performance under fire of plain mortar, steel-reinforced mortar and ferrocement while Group B was conducted to investigate the influence of wire mesh content by varying the volume fraction of wire mesh from 0%, 0.54%, 1.63% and 4.36% which were equivalent to 0, 2, 6 and 16 layers of hexagonal wire mesh, respectively. Finally Group C was conducted to study the effect of the mortar cover of 1.5, 2.0 and 2.5 mm. Series 3, which was used as the control series for all groups, consisted of skeletal steel and had volume fraction of wire mesh and mortar cover of 1.63% and 1.5 mm, respectively. The details of the specimen series and their groups are summarized and shown in Table 1. For each series, seven identical ferrocement specimens were cast, of which three specimens were tested without exposure to fire and four specimens were subjected to a temperature envelope where the temperature was gradually increased to a maximum of 1060 °C within a duration of 3 h. The mechanical properties were obtained by taking the average of these specimens. For visual inspection, all damages were recorded and the typical damage patterns were identified. The visible effects of the main parameters were compared based on the typical damage patterns.

Table 2
Properties of wire mesh

Gauge no.	21
Wire diameter (mm)	0.78
Opening (mm)	19.0
Weight per unit area of mesh (kg/m^2)	0.535
Volume per unit area of mesh ($\times 10^{-5}$ m^3/m^2)	6.82
Surface area per unit area of mesh (m^2/m^2)	0.339

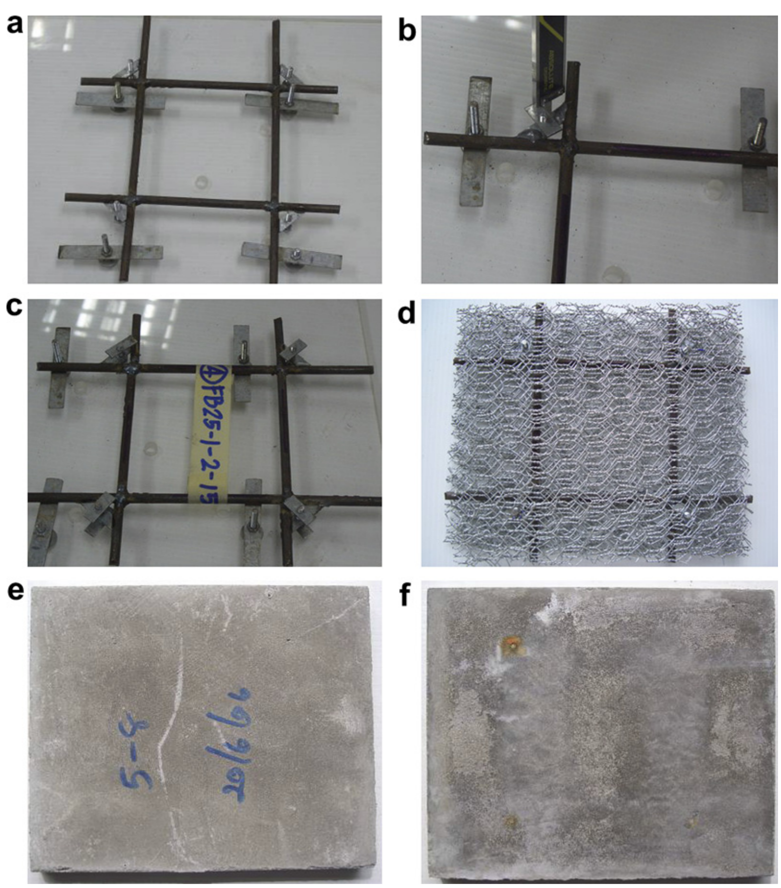


Fig. 1. Steps in the fabrication of ferrocement. (a) Position of skeletal steel, (b) Position of galvanized plate spacer, (c) Skeletal steel with galvanized plate spacer before placing wire mesh, (d) Installation of wire mesh, (e) Finishing surface (to be subjected to fire), (f) Bottom surface.

2.1. Materials used

The ferrocement reinforcement cage consisted of skeletal steel and wire mesh. Ordinary steel bar having a diameter of 6 mm spaced at 100 mm center-to-center was used as skeletal steel in the longitudinal and transverse direction. The longitudinal and transverse skeletal steel were welded together in the same plane; in other words, there was no overlapping of skeletal steel. The volume fraction of skeletal steel was 2.14%. Galvanized hexagonal steel wire meshes were used as mesh reinforcement, and the numbers of mesh layers were 2, 6 and 16 layers corresponding to the volume fractions of 0.54%, 1.63% and 4.36%, respectively. The wire mesh layers were placed in such a way that the mesh opening was minimized. The properties of galvanized hexagonal wire mesh used in this experiment are shown in Table 2. The positions of the mesh layers were controlled by using galvanized plate spacers, as shown in Fig. 1, in order to obtain accurate mortar cover. The mortar cover of ferrocement varied from 1.5 to 2.5 mm. The control series consisted of one layer of skeletal steel, six layers of wire mesh, and mortar cover of 1.5 mm. The ferrocement mortar consisted of ordinary portland cement (OPC) Type I and natural river sand passing sieve No. 16 [18] mixed at a ratio of 1:2 by weight, and the water–cement ratio was 0.48 by weight. After mixing, the mortar was cast in steel molds over the reinforcement cage and compacted using a vibrating table. The dimensions of all specimens were 200 mm × 240 mm × 25 mm (width × length × thickness). All ferrocement specimens were cured for a period of seven days and subsequently the specimens were allowed to air-dry until the time of testing.

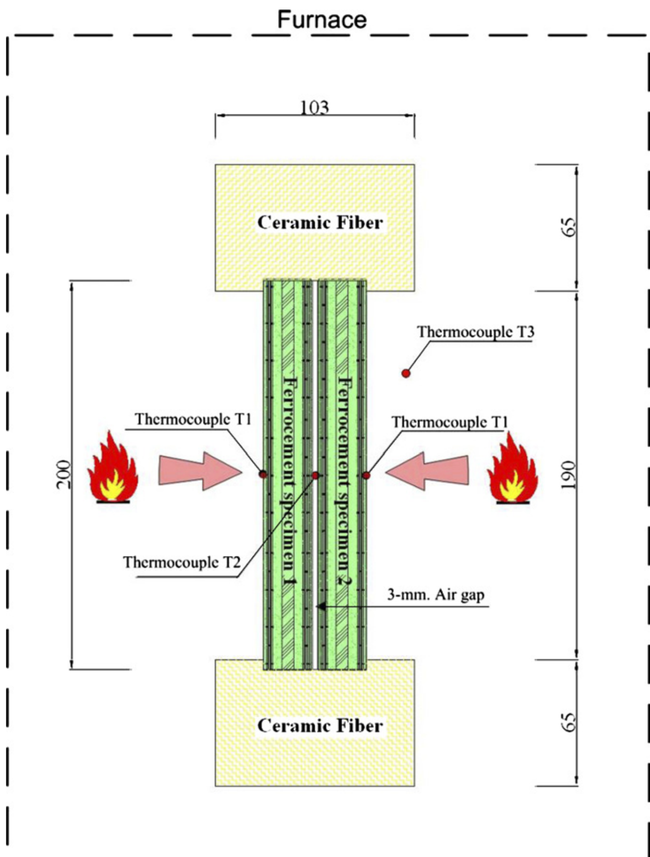


Fig. 2. Schematic diagram of ferrocement specimen based on sandwich-sample configuration.

2.2. Preliminary observation

Before exposure to fire, all ferrocement specimens were weighed and graphical details were recorded for comparison with ferrocement after exposure to fire.

2.3. Fire exposure

A sandwich-sample configuration of ferrocement which consisted of edge insulation was put in the temperature controlled electrical furnace, as shown in Figs. 2 and 3. This configuration was set up in such a way that the heat transfer characteristics of the ferrocement sample were similar to ferrocement jackets exposed to fire. The 3 mm air

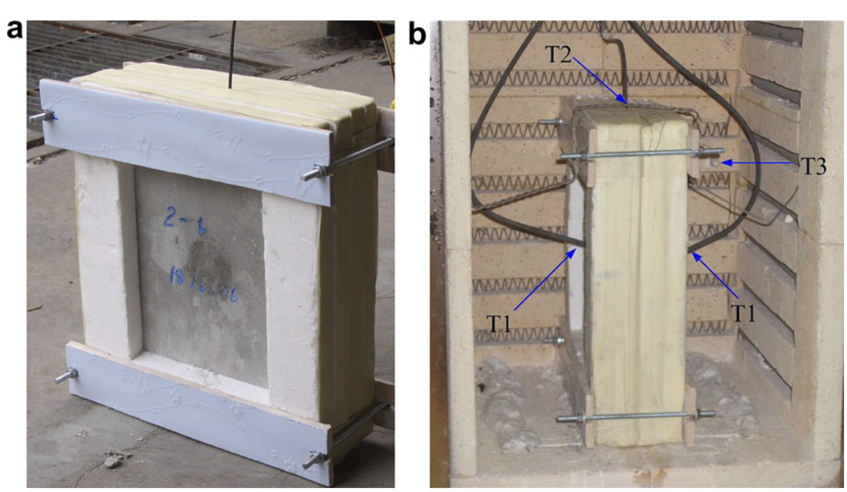


Fig. 3. The arrangement of ferrocement jacket simulation in experimental furnace. (a) Actual photographs of sandwich-sample configuration of the ferrocement specimen, (b) Thermocouple arrangement.

gap between samples was provided solely for thermocouple installation. The temperature envelope was controlled to be equivalent to ASTM E119 [19] by equal time–temperature relation area and maximum temperature concepts [20] as illustrated in Fig. 4. A 60 mm ceramic fiber insulation edge was used to control the direction of the heat flow through the ferrocement specimen so that the heat transmission could be considered as a 1-D heat flow from the hot side to the cold side. The change in temperature during the test was measured by using thermocouple type K and recorded every 30 s by using a computerized data logger. There were three thermocouples installed at the exposed surface of the ferrocement specimen. Two thermocouples (T1) were used to monitor the temperature of exposed ferrocement surfaces whereas one thermocouple (T3) was used to measure the temperature inside the furnace. Another thermocouple (T2) was provided between the two specimens to monitor the unexposed surface temperature. After fire exposure, the specimens were left to cool down to room temperature in the furnace before the tests of their physical and mechanical properties were conducted.

2.4. Visual inspection and mechanical properties tests

The texture, color, cracking, spalling and failure patterns of the ferrocement specimens after fire exposure were obtained by visual inspection. The mechanical properties of ferrocement before and after fire exposure, namely the flexural strength and toughness, were obtained by the flexural strength test with center-point loading in accordance with ASTM C293-02 [17]. The span length for the test was 200 mm.

2.5. Deterioration of ferrocement after fire exposure

In order to determine the degree of deterioration of the ferrocement specimen, the post-fire flexural strength and toughness were calculated as a percentage of the reference properties (original properties). Toughness or the energy absorption capacity of ferrocement in bending was defined as the area under the load-midspan deflection curve. In this paper, toughness was calculated up to a midspan deflection of 25 mm. With regard to visual inspection, the degree of damage was evaluated by the severity of cracking, crazing and spalling.

3. Experimental results and discussion

3.1. Mechanical properties

The percentages of residual flexural strength and toughness of post-fire ferrocement specimens, which are determined from the average of three original specimens and four post-fire specimens, are summarized and shown in Table 3. Test results showed that the incorporation of wire mesh not only improved the original mechanical properties (before exposure to fire) of ferrocement but also significantly enhanced post-fire mechanical properties as shown in Table 3A and Fig. 5. Besides being used as repairing and strengthening material for reinforced concrete members, a ferrocement jacket was found to offer additional resistance against fire as evidenced in Fig. 5. In this figure, the plain mortar which represents the concrete cover loses its flexural strength and toughness almost entirely, whereas for the ferrocement jacket the remaining flexural strength and toughness were found to be approximately 18% of its original strength. The effects of volume fraction of wire mesh and mortar cover on the post-fire mechanical properties of ferrocement can be summarized as follows:

3.1.1. Volume fraction of wire mesh

An experimental investigation using a uniform mortar cover of 1.5 mm (except for the case of 0% volume fraction) was conducted to investigate the influence of the volume fraction by varying the volume fraction of wire mesh from 0%, 0.54%, 1.63% and 4.36%, which were equivalent to 0,

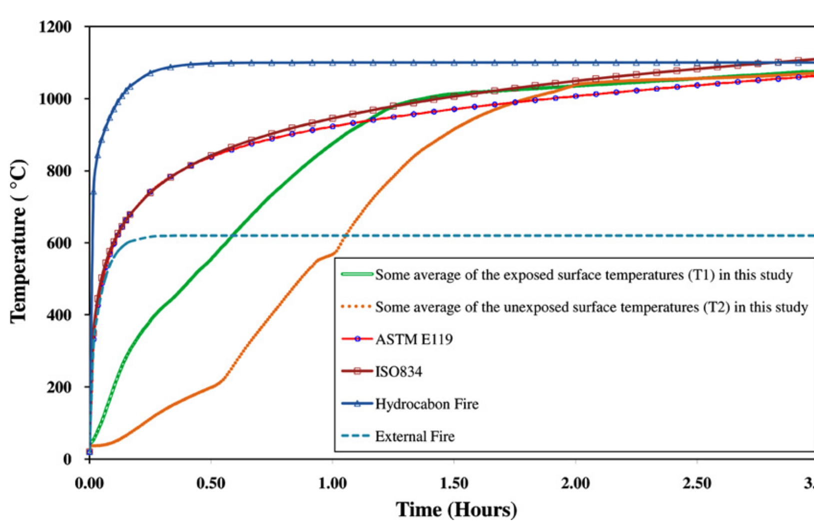


Fig. 4. Experimental time–temperature envelope V.S. ASTM E119 and other fire loading.

Table 3
Test results of mechanical properties of ferrocement

Series ID	Condition	Flexural strength (MPa)			Strength ratio[a]	Toughness, N-m[b]			Toughness ratio[c]
		Max	Min	Average		Max	Min	Average	
A. Effect of reinforcement incorporation									
FA25-0-0-NA (Plain mortar)	Unheated	8.6	6.3	7.5	0.29	1.5	0.5	1.00	0.01
	After fire exposure	0.2	0.1	0.2	0.01	0.1	0.0	0.06	0.00
	% Remaining			2				6	
FA25-1-0-NA (Mortar + skeletal steel)	Unheated	15.1	12.5	13.8	0.53	138	57	98	0.54
	After fire exposure	0.4	0.3	0.4	0.01	3	2	2	0.01
	% Remaining			3				2	
FA25-1-6-15	Unheated	26.1	25.6	25.8	1.00	194	170	182	1.00
	After fire exposure	5.6	4.0	4.6	0.18	41	25	31	0.17
	%Remaining			18				17	
B. Effect of the volume fraction of wire mesh									
FA25-1-0- NA (0 %)	Unheated	15.1	12.5	13.8	0.53	138	57	98	0.54
	After fire exposure	0.4	0.3	0.4	0.01	3	2	2	0.01
	%Remaining			3				2	
FB25-1-2-15 (0.54 %)	Unheated	19.0	17.7	18.4	0.71	147	136	142	0.78
	After fire exposure	5.1	3.7	4.5	0.17	36	24	30	0.16
	%Remaining			25				21	
FA25-1-6-15 (1.63 %)	Unheated	26.1	25.6	25.8	1.00	194	170	182	1.00
	After fire exposure	5.6	4.0	4.6	0.18	41	25	31	0.17
	%Remaining			18				17	
FB25-1-16-15 (4.36 %)	Unheated	35.8	35.5	35.7	1.38	303	287	295	1.62
	After fire exposure	8.0	7.5	7.7	0.30	55	55	55	0.30
	%Remaining			22				19	
C. Effect of the mortar cover									
FA25-1-6-15 (1.5 mm)	Unheated	26.1	25.6	25.8	1.00	194	170	182	1.00
	After fire exposure	5.6	4.0	4.6	0.18	41	25	31	0.17
	% Remaining			18				17	
FC25-1-6-20 (2.0 mm)	Unheated	26.5	22.1	23.9	0.92	189	158	170	0.93
	After fire exposure	4.8	4.2	4.6	0.18	38	24	33	0.18
	%Remaining			19				20	
FC25-1-6-25 (2.5 mm)	Unheated	26.6	22.5	24.5	0.95	186	139	162	0.89
	After fire exposure	5.1	3.8	4.4	0.17	35	27	30	0.16
	%Remaining			18				18	

[a] Strength ratio is the ratio of the flexural strength of investigated specimen to the original flexural strength of controlled series.
[b] Toughness at 25 mm midspan deflection.
[c] Toughness ratio is the ratio of the toughness of investigated specimen to the original toughness of controlled series.

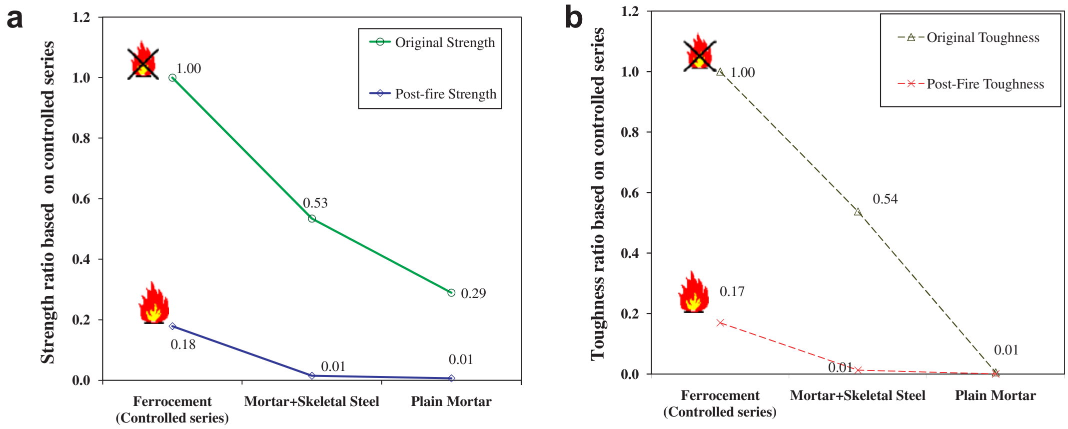


Fig. 5. Effects of reinforcement incorporation on relative flexural strength and toughness of ferrocement.

2, 6 and 16 layers of hexagonal wire mesh, respectively. Before exposure to fire, it was noted that an increase in wire mesh content significantly increased the flexural strength and toughness of ferrocement. However, the post-fire flexural strength and toughness of ferrocement were barely dependent on the content of wire mesh as shown in Fig. 6. Among the three volume fractions investigated in this study, it was found that ferrocement containing 0.54% volume fraction produced the highest residual property as shown in Fig. 7. Thus, it can be seen that using high wire mesh content is not the right solution to improve the post-fire flexural strength and toughness of the ferrocement jacket; in other words the post-fire mechanical properties of the ferrocement jacket only slightly increased as the volume fraction of wire mesh was increased. Although ACI committee 549 [21] suggested the minimum volume fraction of reinforcement to be 1.8% (not including skeletal steel in computing the resistance of the bending member), in this study the use of 0.54% of wire mesh content achieved the same level of residual mechanical properties as 1.8% of wire mesh content, as shown in Fig. 6. This phenomenon can be explained by the fact that steel wire mesh regains strength on cooling [6,9], therefore, it has the ability to confine core mortar in the ferrocement specimen. Kodur [3,4] concluded that additional confinement in the core of high-strength concrete columns can enhance its fire performance. The confining action of the top and bottom layers of steel wire mesh on core mortar leads to improvement of post-fire flexural strength and toughness (18% and 17% of original, respectively) compared with plain mortar (2% and 6% of original, respectively). However, for specimens consisting of only skeletal steel and mortar there is no confinement, therefore, their post-fire mechanical properties are more or less the same as plain mortar. Although an increase in the volume fraction of wire mesh causes a better degree of confinement in the core mortar, a higher volume fraction of wire mesh (>0.54%) induces delamination of mortar and results in in-plane cracking.

3.1.2. Mortar cover

An experimental investigation using six layers of wire mesh corresponding to a volume fraction of 1.63% was conducted to investigate the influence of mortar covers of 1.5, 2.0 and 2.5 mm. Before exposure to fire, the lower

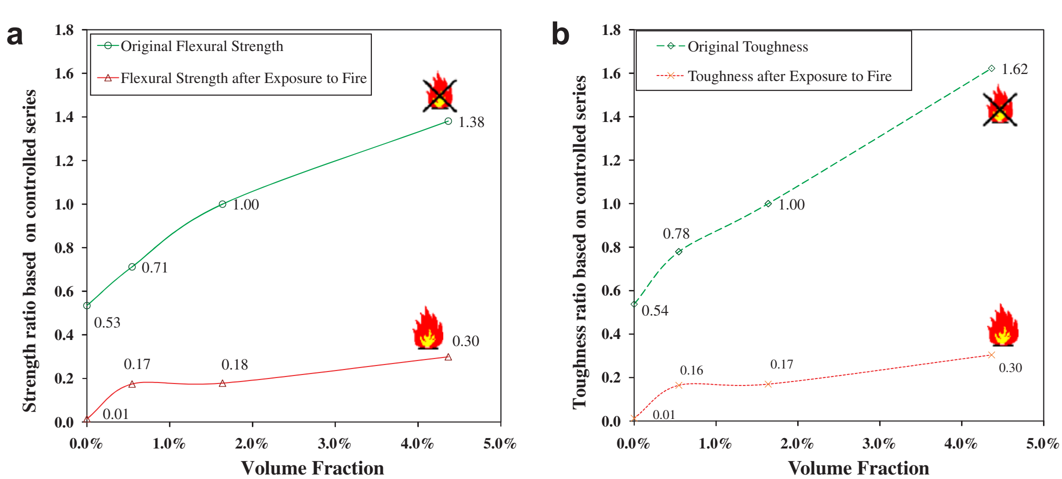


Fig. 6. Effects of volume fraction on flexural strength and toughness of ferrocement before and after exposure to fire based on equal thickness and mortar cover.

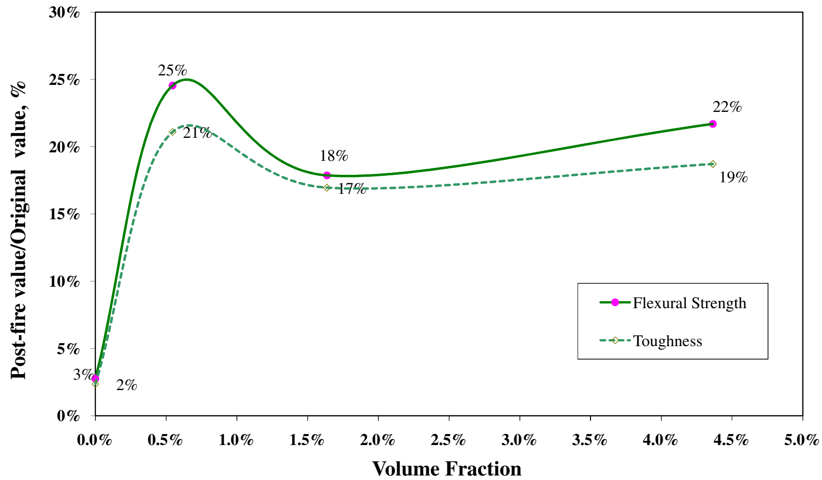


Fig. 7. Effect of the volume fraction of wire mesh on relative mechanical properties of ferrocement based on equal thickness and mortar covering.

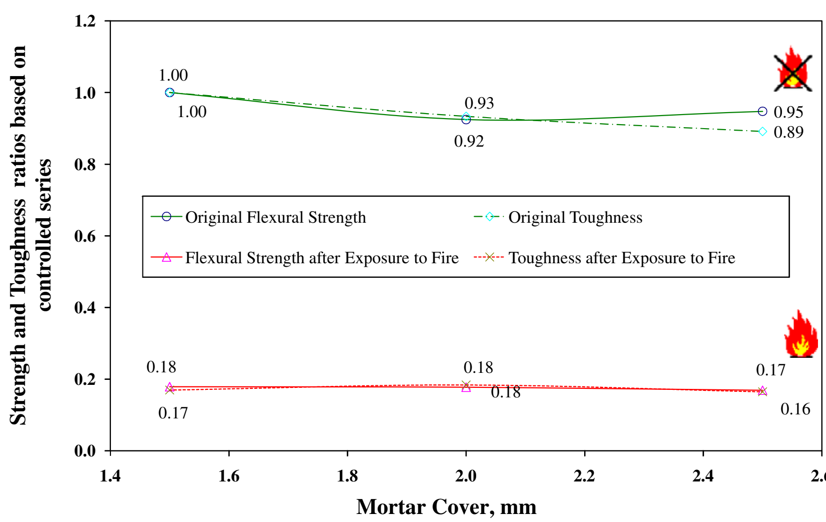


Fig. 8. Effect of mortar cover on flexural strength and toughness of ferrocement before and after exposure to fire based on equal thickness and wire mesh content.

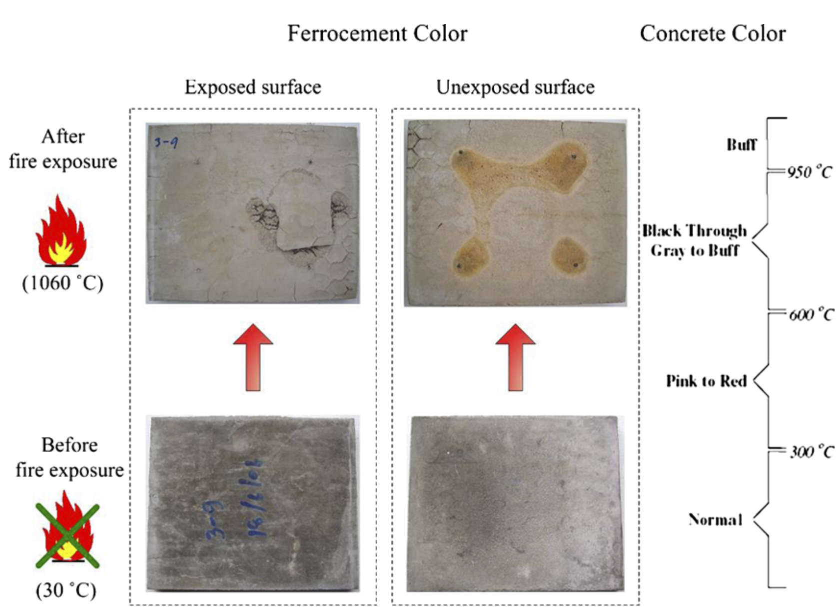


Fig. 9. Color change of ferrocement as compared with concrete color given by Georgali and Tsakiridis [22].

mortar cover exhibited higher flexural strength due to the fact that the lever arm of wire mesh layers was decreased as the mortar cover was increased since all ferrocement specimens possessed identical thickness. After exposure to fire, the remaining flexural strength and toughness, which was approximately 18% of its original value, showed the same trend as that of unheated specimens, as shown in Fig. 8. However, the difference in mechanical properties of ferrocement having different mortar cover thicknesses was found to be insignificant. Therefore, it could be said that mortar cover had no significant influence on the flexural strength and toughness of the ferrocement jacket both before and after exposure to fire.

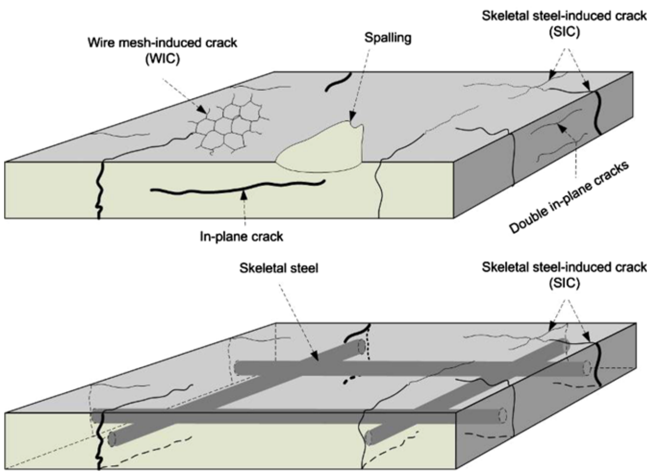
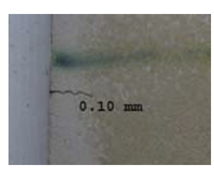
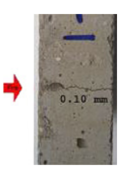
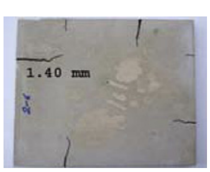
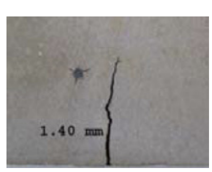
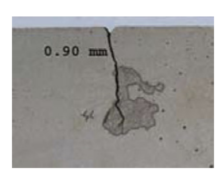
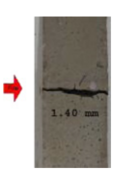
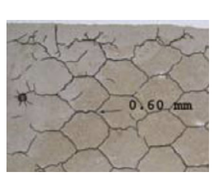
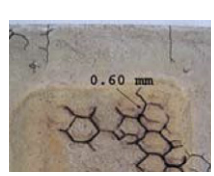
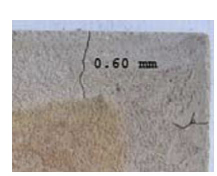
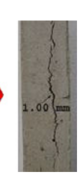


Fig. 10. Schematic diagrams of crack patterns.

3.2. Visual inspection

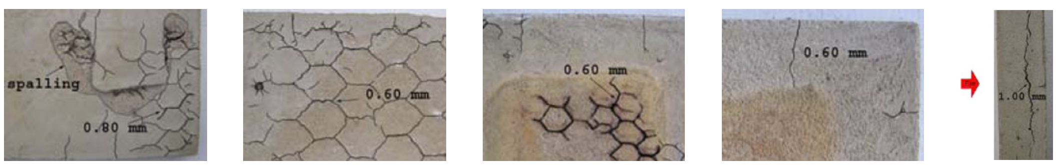
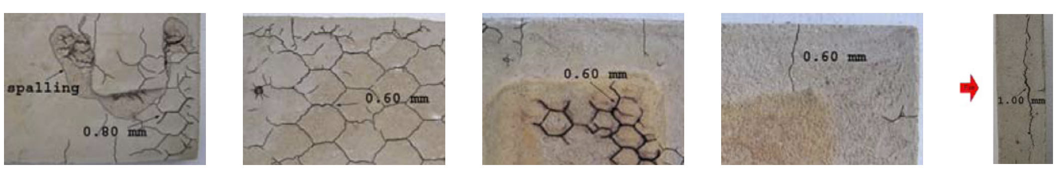
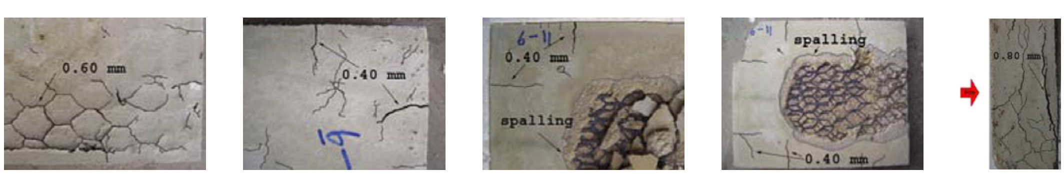
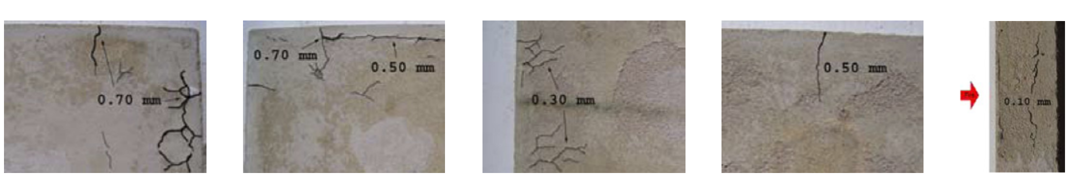
The color changing, cracking, crazing and damage patterns of ferrocement specimens after exposure to fire, which are obtained from four post-fire specimens, are summarized and shown in Figs. 9,10 and Table 4. The color of the ferrocement surface after fire exposure was found to be lighter than before fire exposure, and the changes corresponded to the color changes of concrete subjected to high temperature as proposed by Georgali and Tsakiridis [22]. The results are shown in Fig. 9. Without wire mesh, the use of skeletal steel-induced cracks along the skeletal steel, which was caused by the incompatibility of the thermal expansion/shrinkage between mortar and skeletal steel, and this will be referred to as skeletal steel-induced crack (SIC) as shown in Fig. 10. Moreover, it was found that the incorporation of wire mesh reduced the extent and width of SIC; however, it induced in-plane cracking and surface cracking which looked like the shape of the hexagonal wire mesh; this type of cracking will be referred to as wire mesh-induced crack (WIC) as shown in Fig. 10 and Table 4A. The effects of volume fraction of wire mesh and mortar cover on cracking, crazing and damage to ferrocement after exposure to fire can be summarized as follows:

Table 4
Damage and crack patterns of ferrocement specimen after exposure to fire

Series	Damage patterns of ferrocement specimen exposed to fire				
ID	Exposed surface		Unexposed surface		Side view of samples
A. Effect of reinforcement incorporation					
FA25-0-0-NA					
FA25-1-0-NA					
FA25-1-6-15					

(*continued on next page*)

Table 4 (*continued*)

Series	Damage patterns of ferrocement specimen exposed to fire		
ID	Exposed surface	Unexposed surface	Side view of samples
B. Effect of the volume fraction of wire mesh			
FA25-1-0-NA (0%)			
FA25-1-2-15 (0.54%)			
FA25-1-6-15 (1.63%)			
FA25-1-16-15 (4.36%)			
C. Effect of mortar cover			
FA25-1-6-15 (1.5 mm)			
FA25-1-6-20 (2.0 mm)			
FA25-1-6-25 (2.5 mm)			

Note: Maximum crack width is indicated near the crack lines.

3.2.1. Volume fraction of wire mesh

An experimental investigation using a uniform mortar cover of 1.5 mm and volume fractions of 0%, 0.54%, 1.63% and 4.36%, which correspond to 0, 2, 6 and 16 layers of hexagonal wire mesh, respectively, was conducted to investigate the effect of the volume fraction on cracking, crazing, and damage. It was found that an increase in wire mesh content not only induced more visible damage but also changed the damage pattern. At 0% volume fraction, only a large SIC was found on the ferrocement specimen. An increase in the volume fraction of wire mesh up to 0.54% led to reduction in the SIC's width; however, in-plane cracking and WIC were initiated. WICs and the magnitude of the in-plane cracks grew as the wire mesh content was increased. It is interesting to observe that surface spalling of ferrocement started to occur at a volume fraction of 1.63%. At the maximum wire mesh content (4.63%), both more spalling and in-plane cracking were observed on some of the specimens as shown in Table 4B.

3.2.2. Mortar cover

The ferrocement specimen consisting of six layers of wire mesh (1.63% volume fraction) and the mortar covers of 1.5, 2.0 and 2.5 mm were exposed to fire in order to investigate the effects of the mortar cover on cracking and damage. It was found that an increase in the mortar cover led to a decrease in in-plane crack width and the number of WICs. Only a few WICs and small in-plane cracks still remained at a mortar cover of 2.5 mm. Regarding SICs, their magnitude decreased as the mortar cover was increased from 1.5 to 2.0 mm; subsequently, the magnitude of the SICs increased slightly, as shown in Table 4C. Regarding the cracking mentioned before, it could be said that more visible damage to the ferrocement jacket after exposure to fire occurred on thinner mortar cover. However, the visible cracking did not indicate the degree of mechanical deterioration, which slightly decreased as mortar cover increased.

This phenomenon could be explained by the fact that the difference in thermal expansion of the ferrocement mortar and skeletal steel led to mortar-skeletal steel interface cracking which is called skeletal steel-induced cracking (exhibited on series FA25-1-0-NA in Table 4). It was noted that the use of wire mesh can more or less eliminate this type of cracking. On the other hand, the expansion of the wire diameter resulted in WICs, in-plane cracking and spalling, which was different from the use of steel fiber in concrete [3,4,23]. It can be concluded that the use of volume fraction of wire mesh can result in higher in-plane cracking and spalling. However, the increase in mortar cover was found to be reduced with the expansion of wire mesh. As a result, in-plane cracking and WIC was reduced.

4. Conclusion

The influence of the volume fraction of wire mesh and mortar cover on post-fire mechanical properties, namely flexural strength and toughness including cracking patterns of ferrocement jackets, were experimentally investigated. The following conclusions can be drawn:

(1) Besides being useful as strengthening materials, the ferrocement jacket was found to be a satisfactory solution for fire protection due to its post-fire flexural strength and toughness compared with plain mortar or concrete cover.
(2) Even though an increase in wire mesh content significantly improved the flexural strength and toughness of ferrocement under normal conditions, it was found that after fire exposure the content of wire mesh is no longer significant to these two mechanical properties. Using a wire mesh content of only 0.54% can achieve the same level of residual strength as the minimum suggested wire mesh content of 1.8% given by ACI committee 549 [21]. Moreover, a higher volume fraction of wire mesh resulted in more visible cracking.
(3) For the range of mortar cover investigated, mortar covers had negligible influence on both the flexural strength and toughness of a ferrocement jacket under both normal and after fire exposures. However, more visible damage of ferrocement jacket after exposure to fire occurred in ferrocement with thinner mortar cover.

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