Performance of Fiber Light-Weight Aggregate Concrete Exposed to Elevated Temperatures

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Abstract

Two major problems arise when concrete is exposed to elevated temperatures. One is the deterioration in mechanical properties of concrete and the other problem is spalling of concrete. In recent times, the inclusion of polypropylene fibers had been reported to be a feasible method to prevent spalling of concrete subjected to elevated temperature. Additional problems arise due to the fact that by adding polypropylene fibers, the residual properties of heated concrete may be adversely affected. The essential objective of this work is to investigate the effect of incorporation of polypropylene fibers or/and steel fibers on the residual properties of lightweight concrete made from porcelinite aggregate after subjected to elevated temperatures. The concrete specimens heated to target temperatures of 100, 200, 400, 600 and 800 ^{o}C, at a rate of 10 ^{o}C per minute. When the target temperature was reached, the specimens were kept at that temperature for 2 hours and then allowed to cool to room temperature by natural cooling. For each type of concrete, compressive strength, splitting tensile strength, static modulus of elasticity, and thermal expansion strains were determined before and after exposing the concrete to the target elevated temperatures. Experimental results indicated that polypropylene fiber-reinforced LWAC showed more reduction in its residual mechanical properties compared to plain LWAC. These different are more pronounced at exposure temperature of 200 and 400 ^{o}C. Average differences of 30,25 and 20 percent were observed in static modulus of elasticity, splitting tensile strength and compressive strength respectively, for specimens heated up to 400 ^{o}C. The addition of steel fibers inside the polypropylene fiber concrete would improve the residual mechanical properties of heated concrete at temperature range 200 to 600 ^{o}C. On average, the improvement ranged from 9 to 20 percent.

Keywords: Lightweight Aggregate Concrete, Porcelinite Aggregate, Elevated Temperature, Steel Fiber, Polypropylene Fiber

أداء الخرسانة خفيفة الوزن الحاوية على الألياف والمعرضة إلى درجات حرارة عالية

الخلاصة

هنالك مشكلتان رئيسيتان عند تعرض الخرسانة إلى درجات الحرارة العالية. المشكلة ألأولى هي تدهور الخواص الميكانيكية للخرسانة و المشكلة الأخرى هي تشظي الخرسانة. لقد وجد مؤخرا" إن إضافة ألياف البولي بروبلين إلى الخرسانة هي طريقة مناسبة لمنع تشظي الخرسانة عند تعرضها إلى درجات الحرارة العالية. تظهر مشكلة أخرى نتيجة انصهار هذه الألياف حيث توثر سلبا" على خواص الخرسانة المعرضة للحرارة العالية. إن الغرض الرئيسي من هذا البحث هو التعرف على تأثير إضافة ألياف البولي بروبلين و/او ألياف الحديد على أداء الخرسانة خفيفة

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الوزن المنتجة من ركام البورسيلينايت بعد تعرضها إلى درجات الحرارة العاليـــة. تـــم تـــسخين النماذج الخراسانية إلى درجات حرارة 100, 200, 400, 600 و 800 م° و بمعدل تسخين 10 م° /دقيقة وتم الإبقاء على درجة الحرارة المطلوبة لفترة ساعتين بعدها تم تبريدها بشكل طبيعـــي إلى درجة حرارة الغرفة. تم في هذا البحث إجراء عدة فحوص تـــضمنت مقاومـــة الانـــضغاط, مقاومة الشد الانشطاري, معامل المرونة الساكن, والتمدد الحراري قبل وبعد تعرض النماذج إلى الحرارة العالية. سببت إضافة ألياف البولي بروبلين أكثر انخفاضا فـــي الخـــواص الميكانيكيـــة للخرسانة المسخنة مقارنة مع الخرسانة غير الحاوية على ألياف البولي بروبلين. هذا الانخفـــاض كان أكثر وضوحا عند درجات حرارة التعرض 200 و 400 م° حيث كان الاختلاف حوالي 30, 25 و 20 % في معامل المرونة الساكن, مقاومة الشد الانشطاري ومقاومـــة الانـــضغاط علـــى التوالي للنماذج المسخنة لغاية 400 م° .أدت إضافة ألياف الحديد إلى الخرسانة الحاويـــة علـــى ألياف البولي بروبلين إلى تحسين الخواص الميكانيكية للخرسانة المعرضة إلى درجـــات حـــرارة 200 إلى 600 م°, حيث كان معدل التحسن من 9 إلى 20 % .

1. Introduction:

The use of lightweight aggregate in concrete has many advantages. These may include: a) reduction of dead load that may result in reduced footings size and significant reduction in reinforcement, b) lighter and smaller precast element needing smaller and less expensive handling and transporting equipment, c) reduction in the sizes of columns and slab and beam dimensions that result in larger space availability, and d) high thermal insulation.

Lightweight aggregate concrete has become more popular in recent years owing to the tremendous advantages it offers over the conventional concrete. Structural LWAC is being used in many applications such as buildings, bridges, parking garages, petroleum industry, offshore installations, power plants, transportation systems etc.

2. Research Significant

Given the many benefits of LWAC and its increased use in structural applications, it is essential that the fundamental behavior of LWAC at elevated temperatures is understood to ensure that structural fire design involving LWAC will be safe.

3. Concrete under High Temperature:

The advantages of concrete in a fire are two- fold. It is: incombustible (e.g. when compared with wood); and a good insulating material possessing a low thermal diffusivity (e.g. when compared with steel). However, there are two problems of concrete in fire. These are: deterioration in mechanical properties as temperature rises, caused by physicochemical changes in the material during heating and; explosive spalling, which results in loss of material, reduction in section size and exposure of the reinforcing steel to excessive temperatures. Consequently, both the separating/insulating and load-bearing functions of the concrete member could be compromised.

Structural LWAC generally exhibits greater fire resistance than NWAC when exposed to fire conditions. This superior performance is due to combination of lower thermal conductivity (leading to lower temperature rises on exposed surface) and lower coefficient of thermal expansion (leading to lower forces developed under restraint). Some LWA concretes may not exhibit the same level of performance as NWA concrete under severe fire conditions. In these concretes, spalling under fire conditions is one the major concerns. The main reasons for this are that LWAC compared to NWAC has: [1]

I- Higher moisture content (the lightweight aggregates may act like water reservoirs and thus increase the amount of evaporable water).

II- Lower permeability (lead to higher vapor pressure in the LWAC).

III- Lower heat conductivity (lead to higher temperature gradients, in consequence an increase of thermal stresses).

IV- Lower tensile strength at similar water/binder ratios.

V- The relatively low thermal incompatibility between the LWA and cement paste at elevated temperature may lead to reduce the development of microcracks, consequently, resulting in high pore pressure and increasing the possibility of spalling.

In recent time, the inclusion of polypropylene fibers had been reported to be a feasible method to prevent spalling of concrete subjected to elevated temperature [2**].** The mechanism of the polypropylene fibers to prevent the risk of spalling is not yet understood. It seems that either continues canals in the concrete when the fibers are melt [3]or the microcracking occur in the concrete when the fibers are heated (large thermal expansion coefficient than of concrete) [4**].**

Additional problems arise due to the fact that by adding polypropylene fibers, the residual properties of heated concrete may be adversely affected [5]. This study presents an attempt to make full improvement possible through the use of fibers by incorporating steel fibers together with polypropylene fibers inside the LWAC mix.

4. Experimental Program:

4.1 Materials:

4.1.1 Cement:

Ordinary Portland cement manufactured by Al-Kufa Cement Factory was used in all mixes throughout this study. The percentage oxide composition and physical properties of the cement indicate that the adopted cement conforms to the **Iraqi specification No.5 /1984** [6]**.**

4.1.2 Fine Aggregate:

Normal weight natural sand brought from Al-Najaf quarry was used as fine aggregate in this work. The physical and chemical tests on sand used throughout this work are shown in **Table (1).** The used sand was within zone II according to the requirements of the **Iraqi specification No.45/1984** [7]**.**

4.1.3 Coarse Aggregate:

Local naturally occurring lightweight aggregate of porcelinite stones was used as coarse aggregate.

The aggregate for each batch was washed by water and spread inside the laboratory in order to bring the aggregate particles to saturated surface dry condition. The grading of coarse porcelinite aggregates, which was adopted throughout this study, is shown in **Table (2)**.

Several physical and chemical properties were determined for coarse porcelinite aggregate. **Table**

(3) lists these properties and their corresponding proper specifications.

4.1.4 Admixtures:

4.1.4.1 High Range Water Reducing Admixture (HRWRA):

A high performance concrete superplasticizer based on modified polycarboxylic ether which is known commercially (GLENIUM 51) was used throughout this investigation as a (HRWRA). It is a third generation of superplasticizers and it complies with **ASTM 494** Type A and F [8].

4.1.4.2 Condensed Silica Fume (CSF):

Silica fume MS-90 was used in this study. The relative density and surface area of silica fume were 2.12 and 18000 m^2/kg respectively.

4.1.5 Fibers:

Two different types of fibers were used in this study. The content and geometry of fiber were defined according to an analysis made for previous experiments [9,10]

4.1.5.1 Polypropylene Fibers:

Fibrillated polypropylene fibers were used in this study. It was manufactured by CNBM Company (China National Building Materials). **Table (4)** indicates the physical properties of polypropylene fibers used throughout this work.

4.1.5.2 Steel Fibers:

Straight, short cut and brass coated steel fibers were used in this investigation. It was manufactured by CNBM Company. Aspect ratio (L/d= length/diameter) of steel fibers was 65. The density and tensile strength of steel fibers were 7800 kg/m^3 and 2500 MPa respectively.

4.2 Concrete Mixes:

The reference concrete mixture was designed in accordance with **ACI committee 211** [11] to produce a structural LWAC. Ordinary Portland cement of 550 kg/m^3 content, fine aggregate of 500 kg/m^3 and LWA content of 520 kg/m^3 were used in this study. After many trials, one reference mix proportion was used in this study (1:1.13:1.83) by volume. HRWRA was used in all mixes except reference mix (MR), to maintain similar workability slump (110 ±5) mm. Fiber reinforced LWAC mixes were made by using Mix I with polypropylene or/and steel fibers. The silica fume was used as a partial replacement by weight of cement The details of the mixes used throughout this investigation are given in **Table (5).**

4.3 Heating Procedure:

The concrete specimens were demolded the day after casting and stored under water up to the age of 28 days. After that they were exposed to laboratory environment at about 23±2 ^{o}C and 50±5 percent relative humidity up to the age of 56 days. Then, they were heated in an electric furnace to target temperature at a rate of 10 $^{o}C/min$.

During a building fire, variation in rate of heating may be expected to occur, not only from one building to another, but also within a single room and even along a given structural member. According to **Phan** and **Carino** [12], the heating rates used in the reviewed experimental studies varied from 0.2 to 32 $^{o}C/min$. However, the rate of heating was selected to be10 $^{o}C/min$, which was the maximum controllable rate of rise provided by the electric furnace.

All test specimens were placed in the cool furnace, and turned on. When the target temperature was reached, the specimens were kept at that temperature for 2 hours. The specimens were then allowed to cool to room temperature by natural cooling and then removed to be ready for the required test.

4.4 Tests:

4.4.1 Compressive Strength:

The compressive strength test was determined according to the **ASTM C39 -** [13]. This test was conducted on (d=150 mm, h=300 mm) cylinders using an electrical testing machine with a capacity of 2000 kN at loading rate of 15 MPa per minute.

4.4.2 Splitting Tensile Strength:

The splitting tensile strength test was performed according to **ASTM C496 -**[14]. (d=150 mm, h=300 mm) cylinders concrete specimens were used. The specimens were testing using an electrical testing machine with a capacity of 2000 kN.

4.4.3 Static Modulus of Elasticity:

Axial compressive stress-strain relationships were determined, using (d=150 mm, h=300 mm) cylindrical specimens and mechanical strain gauges of effective length equal to 150 mm. Static modulus of elasticity was also determined from this test according to **ASTM C469-**[15]**.**

4.4.4 Volume Change:

This test was carried out in accordance to **ASTM C490** [16]**,** using (100 × 100 × 400) mm prism specimens to measure the change in length of the hardened concrete and using mechanical extensometer.

All specimens were immersed in water for 7 days then two points were defined with demec points on each of two opposite and stored in the laboratory at about (23 ± 2 ^{o}C and 50 ± 5 percent relative humidity) up to the age of 56 days. Many readings, for the change in length of the specimens, were recorded throughout that period. Then the specimens were exposed to the required elevated temperatures and the changes in length were also recorded.

5. Results and Discussions:

5.1 Compressive Strength:

The variation in the compressive strength of fiber- reinforced LWAC for all mixes with respect to temperature is given in **Tables (6)** and shown graphically in **Fig.(1).** The results showed that the compressive strength of both plain LWAC and the fiber-reinforced LWAC decreased with the increase in temperature and the type of fiber has influenced the extent of compressive strength loss.

The test results indicate that, in a temperature range of 200 to 400 ^{o}C, the concrete specimens incorporating 0.25% by volume polypropylene fibers suffered higher loss in compressive strength than that observed for the plain concrete. For 0.25% by volume polypropylene fiber-reinforced concrete, the loss in compressive strength was 30 and 40 percent of the unheated strength while the loss for the plain concrete was of the order of 15 and 22 percent when the specimens were exposed to temperature of 200 and 400 ^{o}C respectively. While for exposed temperatures of 600 and 800 ^{o}C, the percentage drop in compressive strength for both plain and the polypropylene fiber-reinforced concretes was similar.

The reduction in compressive strength of LWAC incorporating polypropylene fibers heated up to 400 ^{o}C can be explained by the fact that, at 160 ^{o}C, the reduction in the volume of polypropylene fibers due to the melting starts to happen. As the temperature increases, the fibers will degrade, beginning to ignite at temperatures close to 360 ^{o}C. At this point, the fibers regress to their constituent materials, and all that remains of individual filaments is soot, which occupies approximately 5% of the original size. This is leading to increased porosity and microcracking causing a decrease of concrete compressive strength. This also explains why the concrete specimens with and without polypropylene fibers exhibited approximately similar reduction in their compressive strength at temperature above 400 ^{o}C. This explanation is supported by visual inspection conducted on heated specimens incorporating polypropylene fiber, which did not detect any fiber after exposure to 400 ^{o}C.

Test results also showed that the presence of steel fibers did not influence the variation of compressive strength when the specimens were exposed to a temperature below 400 ^{o}C. However, with further increase in temperature the compressive strength of steel fiber-reinforced LWAC increased, with increasing fiber content, reaching an average value about of 15 percent greater than plain LWAC at 600 ^{o}C and of about 70 percent of the original compressive strength (at room temperature). This can be attributed to the fact that the presence of steel fibers in concrete helps in limiting the crack growth and propagation at these temperatures range. At 800 ^{o}C, the steel fiber was not effective, and the specimens with and without steel fibers were reduced to the same residual strength. This was attributed to the fact that, at high temperature, the steel fibers probably suffer considerable dimensional variations, disturbing their bonding with the cement matrix or even introducing additional tensile stresses in the concrete, leading to a noticeable deterioration in heated specimens.

In addition it was found that the compressive strength of the hybrid fiber concrete (i.e. steel fiber + polypropylene fiber) was approximately 8 percent lower than that of the plain concrete when exposed to temperatures of 200 and 400 ^{o}C. At 600 ^{o}C, the compressive strength was about 11 percent higher than that observed for the plain concrete. At 800 ^{o}C, the compressive strength of both the hybrid fiber and plain concretes was very similar.

In general, the compressive strength values of the specimens made with binary combination of fibers (steel+polypropylene) are greater than the compressive strength of the specimens containing polypropylene fibers only. This difference is particularly noticeable in the temperatures 200,400 and 600 ^{o}C, **Fig. (1)**. For example the 0.25% polypropylene+1.0% steel fibers concrete specimens gave about 10, 13 and 14 percent increase in compressive strength at 200, 400 and 600 ^{o}C respectively compared with the polypropylene fiber concrete. This may be attributed to the fact that the formation of microcracks caused by the melting of the polypropylene fibers can be repressed by the presence of steel fibers[4].

5.2 Splitting Tensile Strength:

The test results of the splitting tensile strength of various types of fiber-reinforced LWAC exposed to different temperatures are given in

Table (7) and shown graphically in **Fig. (2**).

As shown in **Fig. (2)**, the loss of splitting tensile strength resulting from exposure to elevated temperature was higher for polypropylene fiber- reinforced LWAC compared to the plain LWAC. This difference is particularly noticeable in the lower temperature range of 200 and 400 °C. For the polypropylene fiber concrete, the loss in tensile strength was of the order of 20 and 50 percent of the room temperature tensile strength for specimens exposed to temperature of 200 and 400 °C respectively. While for the plain concrete the reduction was 10 and 30 percent respectively. In the temperature range of 600 and 800 °C the specimens with and without polypropylene fibers exhibited similar residual tensile strength. For example at 600 °C the splitting tensile strength values were about 0.7 and 0.81 MPa for plain and polypropylene fiber concrete respectively.

Test results also showed that the presence of steel fibers did not influence the residual splitting tensile strength of concrete exposed to a temperature up to 400 °C. Above this temperature, the splitting tensile strength of steel fiber- reinforced LWAC increased, with increasing fiber content, compared to the plain LWAC tensile strength for the same exposure temperature. For 0.25%, 0.5% and 1.0% by volume steel fiber, the percentages of increase in the tensile strength were about 10, 15 and 27 percent respectively for specimens heated to 600 °C. At 800 °C, the presence of steel fiber had little or no influence on residual splitting tensile strength of LWAC.

In addition it was found that the splitting tensile strength of the hybrid fiber LWAC was about 5 and 10 percent lower than that of the plain LWAC at 200 and 400 °C respectively. At 600 °C, the splitting tensile strength of hybrid fiber LWAC was about 12 percent higher than that observed for the plain LWAC. At 800 °C, the percentage drop in tensile strength for both the hybrid fiber concrete as well as the plain concrete was almost similar.

It is obvious from these results that the addition of steel fibers inside the polypropylene fiber-reinforced concrete would increase the residual splitting tensile strength of heated concrete for exposed temperatures of 200, 400 and 600 °C. For example the tensile strength of the concrete containing 0.25% polypropylene+1.0% steel fibers was about 5, 15 and 18 percent greater than the concrete containing polypropylene fiber only at 200, 400 and 600 °C respectively, **Fig**.(**2**).

5.3 Static Modulus of Elasticity:

The test results of the static modulus of elasticity of fiber-reinforced LWAC for all mixes with respect to elevated temperature is shown in **Table (8)** and plotted in **Fig. (3).**

As shown in **Fig. (3)**, in the temperature range of 200 and 400°C, the polypropylene fiber-reinforced concrete specimens showed a 30 and 70 percent reduction in static modulus of elasticity, while the plain specimens exhibited a 25 and 50 percent loss in modulus of elasticity compared with reference specimens (at room temperature). At exposure temperatures of 600 and

800 °C, all specimens with and without polypropylene fiber exhibited similar residual moduli of elasticity.

Test results also showed that the presence of steel fibers did not influence the variation of elastic modulus for a temperature below 200°C. However above this temperature the elastic modulus of steel fiber-reinforced concrete increased reaching an average value about of 15 percent greater than plain concrete at 400 °C. At exposure temperatures of 600 and 800 °C, the loss in elastic modulus for both the plain concrete as well as steel fiber concrete was very much alike.

In addition it was found that the elastic modulus of the hybrid fiber concrete was about 10 percent lower than that of the plain concrete for a temperature of 200 and 400 °C. At temperature of 600 and 800 °C, the residual elastic modulus of the hybrid concrete was approximately equal to that of plain concrete.

It is obvious from these results that the mixes containing polypropylene fiber showed the lowest elastic modulus, whereas the hybrid mixes showed a higher elastic modulus values than those containing polypropylene fiber only within exposure temperature up to 400 °C. For example the concrete specimens containing 0.25% polypropylene+1.0% steel fibers showed an average increase in static modulus of elasticity of approximately 2.5 and 20 percent over the polypropylene fiber concrete at 200 and 400 °C respectively.

5.4 Thermal Movement (Total Thermal Expansion):

In **Table (9)** and **Fig. (4)**, the variation of thermal expansion with concrete temperature for plain and fiber- reinforced LWAC is compared. Results show that the thermal expansion of polypropylene fiber-reinforced concrete was generally higher than that of plain concrete. This difference is noticeable in the temperature range of 400 to 500 °C. For fiber concrete, the thermal expansion was about 6700×10^{-6} to 11300×10^{-6} while for plain concrete it was about 4800×10^{-6} to 7200×10^{-6}. This may be attributed to the fact that the polypropylene fibers have higher thermal coefficients than the LWAC, introduce incompatibilities in movement between the LWA concrete and the fiber at these elevated temperatures. This was observed by the formation of fine cracks on the surface of concrete specimens containing polypropylene fibers after heat cycling and also by residual thermal expansion of fiber concrete after cooling from 500 °C, where it was about 75 percent higher than that of the plain concrete.

Test results also showed that the steel fiber- reinforced concrete has similar thermal expansion as that of plain concrete in the temperature range examined. The same behavior for normal weight concrete was observed by **Kodur** and **Sultan,** [17]**.**

In addition it was found that the thermal expansion strains of hybrid fiber concrete were slightly higher than those of plain concrete in the temperature range investigate. For example, at 400 °C the thermal expansion strains were 4800×10^{-6}

and 5351×10^{-6} for plain and 0.25% polypropylene+1.0% steel fibers concretes respectively.

Generally, the addition of steel fibers inside the polypropylene fiber-reinforced concrete would decrease the thermal expansion of heated concrete indicating that the steel fibers were restraining cracking induced by thermal incompatibility between polypropylene fibers and the LWAC, **Fig.(4)**.

Conclusions:

Within the limitations of materials and testing program employed in this study, some important conclusions can be described in the following sections.

1. Polypropylene fiber-reinforced LWAC showed more reduction in its residual mechanical properties compared to plain LWAC. These differences are more pronounced at exposure temperature of 200 and 400°C. Average differences of 30, 25 and 20 percent were observed in static modulus of elasticity, splitting tensile strength and compressive strength, respectively, for specimens heated up to 400 °C.
2. The presence of steel fibers did not influence the variation of compressive and splitting tensile strengths of LWAC below 400 °C. At 600 °C, the compressive strength and tensile strength of steel fiber-reinforced LWAC were, respectively, about 15 and 18 percent greater than plain LWAC exposed to the same temperature. At 800°C the steel fibers were not effective and the specimens with and without fibers were reduced almost to the same residual mechanical properties. The static elastic modulus of steel fiber-reinforced LWAC was about 15 percent greater than plain concrete at 400 °C. Above this temperature, the loss in elastic modulus for both the plain as well as steel fiber-reinforced concrete was almost similar.
3. The addition of steel fibers inside the polypropylene fiber concrete would improve the residual mechanical properties of heated concrete at temperature range of 200 to 600 °C. On average, the improvement ranged from 9 to 20 percent.
4. The thermal expansion of polypropylene fiber-reinforced LAWC was higher than that of plain LWAC in the temperature range of 400 to 500 °C. The thermal expansion of LWAC was not significantly affected by the presence of steel fiber reinforcement in the temperature range examined. Furthermore, the addition of steel fibers inside the polypropylene fiber-reinforced LWAC would decrease the thermal expansion strain of heated concrete in the 400 °C and 500 °C.

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Table (1) Chemical and physical properties of the used sand

Property	Specification	Result	Limit of I.O.S No. 45/1984
Bulk Specific gravity	ASTM C128-2003	2.53	
Absorption, %	ASTM C128-2003	1.9	
Dry loose unit weight, kg/m^3	ASTM C29-2003	1580	
Sulfate content (as SO_3), %	I.O.S No.45-84	0.08	0.5 (Max.)
Materials finer than 0.075 mm sieve, %	I.O.S No.45-84	1.1	5.0 (Max.)

Table (2) Selected grading of coarse lightweight aggregate

Sieve size (mm)	Selected % passing	% Passing ASTM C330
12.5	100	90-100
9.5	70	40-80
4.75	10	0-20
2.36	0	0-10

Table (3) Chemical and physical properties of porcelinite lightweight aggregate

property	Specification	Test result
Specific gravity	ASTM C127-2003	1.62
Absorption, %	ASTM C127-2003	32
Dry loose unit weight, kg/m^3	ASTM C29-2003	775*
Dry rodded unit weight, kg/m^3	ASTM C29-2003	820
Aggregate crushing value, %	BS 812-Part 110-1990	16
Sulfate content (as SO_3), %	BS 3797-Part 2-1981	0.32**
Staining Materials		
Stain intensity Stain index	ASTM C641-2003	No stain 0

***** Within the limit of ASTM C330 (880 kg/m^3)and BS 3797-Part 2 (960 kg/m^3).
****** Within the limit BS 3979- Part 2 (1.0%)

Table (4) Physical properties of polypropylene fibers used in this study*

Specific gravity	0.91
Fiber diameter	38 µm
Fiber length	12mm
Youngs modulus	3500-3900 MPa
Tensile strength	320-400 MPa
Melting point	160 °C
Elongation at break	12 %˜ 14%

* Manufacturers data

Table (5) Details of the mixes used throughout this study

Type of mix	Fiber volume %		w/c or w/c_m	HRWRA% by wt. of cement	CSF % by wt. of cement	Slump (mm)
	P	S				
MR	-	-	0.44	-	-	55
M I	-	-	0.35	2.00	8	110
MI .25P	0.25	-	0.35	2.25	8	110
MI .25S	-	0.25		2.10		115
MI .5S	-	0.50		2.10		110
MI 1.0S	-	1.00		2.25		115
MI .25P+.25S	0.25	0.25		2.50		105
MI .25P+. 5S	0.25	0.50		2.56		110
MI .25P+1.0S	0.25	1.00		3.00		115

Table (6) Average test results of compressive strength of fiber-reinforced LWAC specimens before and after exposure to various temperatures

Type of mix	Exposure temp. °C	Compressive strength MPa		
		Before heating *	After heating	Residual (%)
MI	23	33.31 *	-	100
	100	33.10	27.14	82
	200	33.52	25.94	85
	400	33.60	26.44	78
	600	33.25	16.62	50
	800	33.36	6.00	18
MI .25P	23	31.38	-	100
	100	31.52	25.21	80
	200	31.09	22.07	71
	400	31.41	18.53	59
	600	31.30	16.27	52
	800	31.28	6.25	20
MI .25S	23	34.94	-	100
	100	34.10	27.62	81
	200	34.76	29.19	84
	400	34.62	27.69	80
	600	34.20	20.52	60
	800	34.96	6.99	20
MI .5S	23	35.06	-	100
	100	35.73	28.58	80
	200	35.35	30.04	85
	400	35.21	28.16	80
	600	35.82	23.28	65
	800	35.15	6.32	18
MI 1.0S	23	36.75	-	100
	100	36.42	29.13	80
	200	36.07	30.65	85
	400	36.05	28.47	79
	600	36.50	25.55	70
	800	36.61	7.32	20
MI .25P+.25S	23	31.86	-	100
	100	31.10	25.50	82
	200	31.57	24.62	78
	400	31.11	21.46	69
	600	31.62	17.39	55
	800	31.71	6.34	20
MIII .25P+.5S	23	31.87	-	100
	100	31.86	25.00	80
	200	31.85	25.48	80
	400	31.80	21.62	68
	600	31.82	19.09	60
	800	31.90	7.01	22

MI .25P+1.0S	23	31.92	-	100
	100	31.98	24.94	78
	200	31.90	26.15	82
	400	31.88	22.31	70
	600	31.96	21.73	68
	800	31.87	5.73	18

* Tested at room temperature after 28day moist curing and 28day air-drying (as control specimens)

Table (7) Average test results of splitting tensile strength of fiber-reinforced LWAC specimens before and after exposure to various temperatures

Type of mix	Exposure temp. °C	Splitting tensile strength MPa		
		Before heating *	After heating	Residual (%)
MI	23	2.09	-	100
	100	2.06	1.95	95
	200	2.11	1.89	90
	400	2.10	1.47	70
	600	2.07	0.70	34
	800	2.06	0.26	13
MI .25P	23	2.73	-	100
	100	2.70	2.43	90
	200	2.75	2.25	82
	400	2.76	1.32	48
	600	2.73	0.81	30
	800	2.70	0.27	10
MI .25S	23	3.18	-	100
	100	3.14	2.01	96
	200	3.21	2.95	92
	400	3.20	2.40	75
	600	3.15	1.41	45
	800	3.18	0.47	15
MI .5S	23	3.72	-	100
	100	3.68	3.49	95
	200	3.75	3.56	95
	400	3.67	2.93	80
	600	3.73	1.86	50
	800	3.69	0.51	14
MI 1.0S	23	4.74	-	100
	100	4.69	4.59	98
	200	4.78	4.30	90
	400	4.76	3.99	84
	600	4.70	2.86	61
	800	4.72	0.75	16
MI .25P+.25S	23	3.61	-	100
	100	3.64	3.32	93
	200	3.60	3.09	85
	400	3.59	2.16	60

	600	3.59	1.61	45
	800	3.20	0.53	15
MI .25P+.5S	23	4.20	-	100
	100	4.15	3.94	95
	200	4.24	3.56	84
	400	4.22	2.65	63
	600	4.17	2.00	48
	800	4.19	0.54	13
MI .25P+1.0S	23	5.26	-	100
	100	5.20	4.94	95
	200	5.31	4.56	86
	400	5.30	3.44	65
	600	5.25	2.62	50
	800	5.22	0.93	18
* Tested at room temperature after 28day moist curing and 28day air-drying (as control specimens)				

Table (8) Average test results of static modulus of elasticity of fiber-reinforced LWAC specimens before and after exposure to various temperatures

Type of mix	Exposure temp. °C	Static modulus of elasticity (10^3)MPa		
		Before heating *	After heating	Residual (%)
MI	23	14.622	-	100
	100	14.563	11.650	80
	200	14.711	11.033	75
	400	14.750	7.375	50
	600	14.571	3.642	25
	800	14.599	0.437	3
MI .25P	23	14.165	-	100
	100	14.094	10.993	78
	200	14.099	9.869	70
	400	14.181	4.254	30
	600	14.175	3.402	24
	800	14.160	0.708	5
MI .25S	23	15.654	-	100
	100	15.732	13.372	85
	200	15.700	13.031	83
	400	15.612	9.679	62
	600	15.670	4.048	26
	800	15.659	0.782	5
MI .5S	23	16.072	-	100
	100	16.007	13.601	85
	200	16.152	13.406	83
	400	16.111	10.633	66
	600	16.050	4.173	26
	800	16.125	1.128	7
MI 1.0S	23	15.770	-	100
	100	15.833	13.616	86
	200	15.760	13.396	85

	400	15.825	11.235	71
	600	15.811	4.743	30
	800	15.791	0.789	5
MI .25P+.25S	23	14.319	-	100
	100	14.390	11.368	79
	200	14.301	8.580	60
	400	14.328	5.158	36
	600	14.311	3.577	25
	800	14.388	0.719	5
MI .25P+.5S	23	14.401	-	100
	100	14.458	11.566	80
	200	14.422	9.662	67
	400	14.445	6.066	42
	600	14.400	3.888	27
	800	14.398	0.575	4
MI .25P+1.0S	23	14.653	-	100
	100	14.579	11.371	78
	200	14.601	10.220	70
	400	14.592	6.566	45
	600	14.588	3.355	23
	800	14.575	0.874	6

***** Tested at room temperature after 28day moist curing and 28day air-drying (as control specimen

Table (9) Average results of thermal expansion strains of fiber-reinforced LWAC exposed to various temperatures

Type of mix	23 °C*	Thermal expansion strains (10^{-6})				
		100 °C	200 °C	400 °C	500 °C	Cooling from 500 °C
MI	-500*	600	1550	4800	7200	2000
MI .25P	-507*	650	1990	6700	11300	3480
MIII .25S	-500*	610	1560	4810	7220	2000
MI .5S	-510*	600	1550	4810	7220	1980
MI 1.0S	-510*	620	1565	4820	7240	1990
MI .25P+.25S	-490*	635	1705	5320	7990	2100
MI .25P+.5S	-495*	640	1710	5350	7992	2050
MI .25P+1.0S	-490*	642	1720	5351	8010	2050

-ve: Contraction

* 56 day drying shrinkage strain of LWAC before exposure to elevated temperature

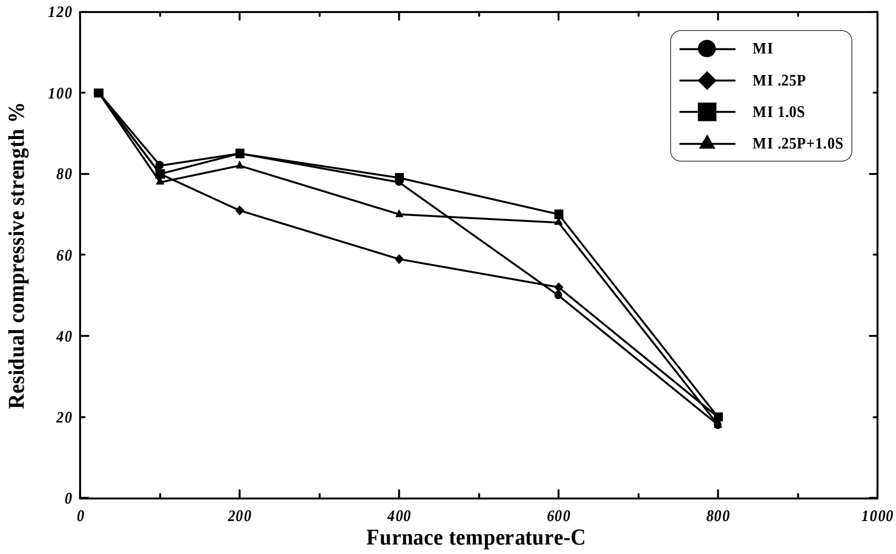

Fig.(1) Effect of polypropylene, steel and hybrid fibers on compressive strength of LWAC exposed to elevated temperatures

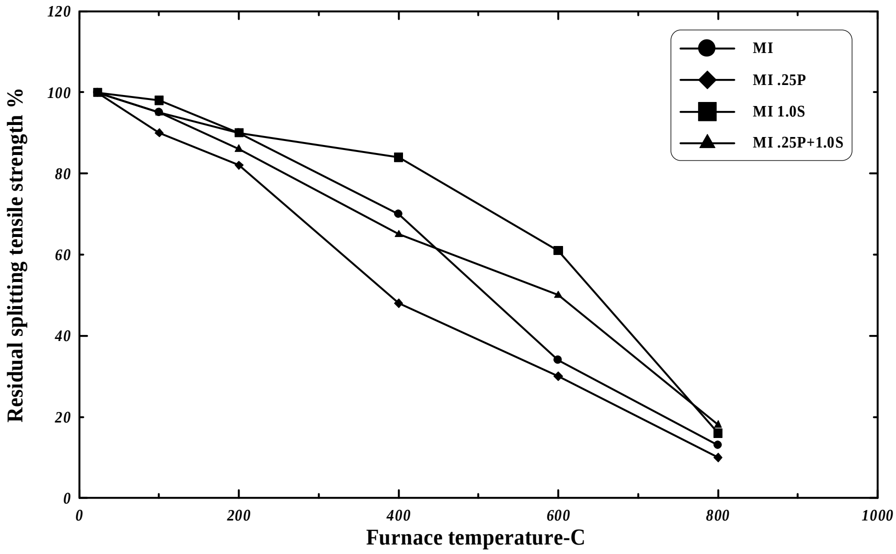

Fig.(2) Effect of polypropylene, steel and hybrid fibers on splitting tensile strength of LWAC exposed to elevated temperatures

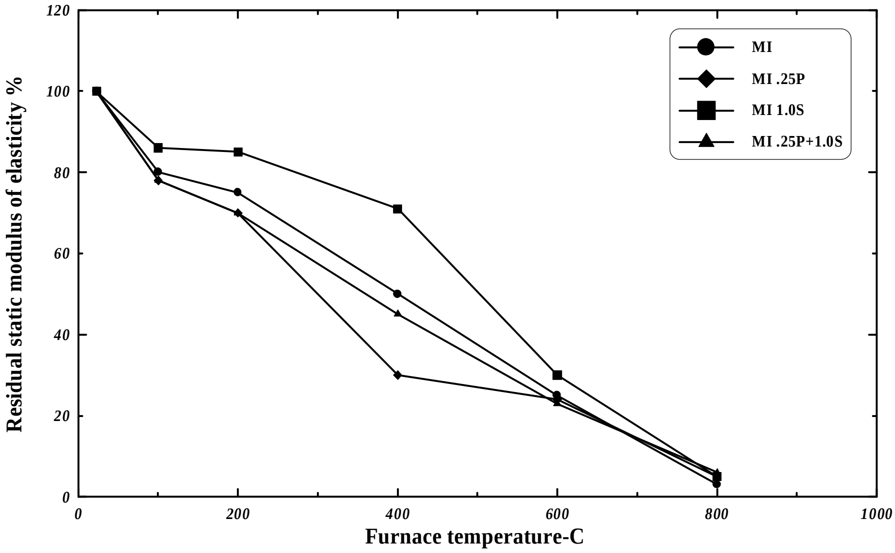

Fig.(3) Effect of polypropylene, steel and hybrid fibers on static modulus of elasticity of LWAC exposed to elevated temperatures

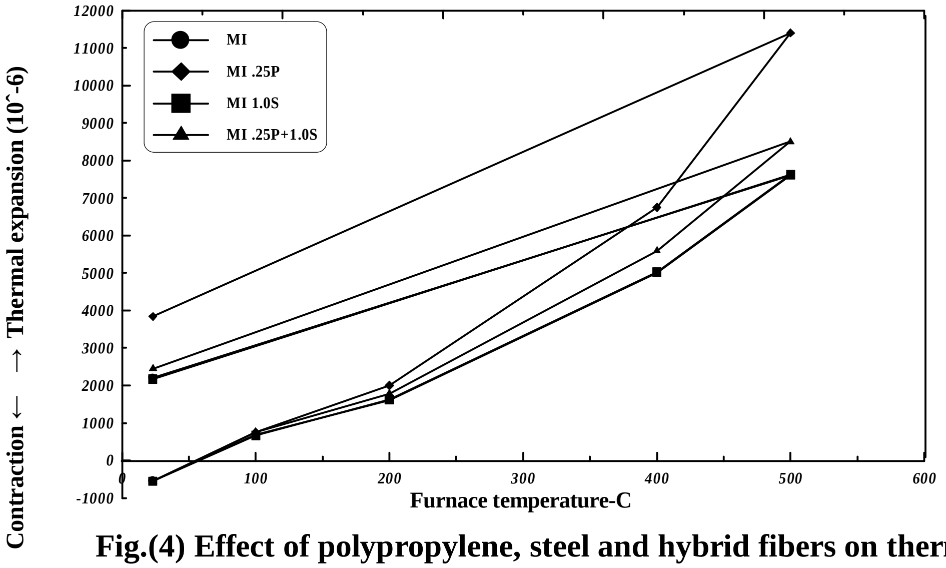

Fig.(4) Effect of polypropylene, steel and hybrid fibers on thermal expansion strains of LWAC exposed to elevated temperatures