LIST OF CHANGES

1) In the text of the paper the lightweight aggregate foamed concrete phrase replaced with “LWAFC”.
   It has been done accordingly.
2) The novelty of the work express clearly in the abstract and introduction.
   The novelty of the present study added to the revised manuscript.
3) The application of the lightweight aggregate foamed concrete added to the manuscript.
   It has been done accordingly.
4) If it is possible investigated the effects of temperature on the mechanical behavior of foamed concrete in the manuscript?
   The effect of temperature on the mechanical properties of concrete requires laboratory equipment, which is not effective for researchers in this study in the current situation.
5) Use of the related references in recent years and the references are corrected according to the format of the journal.
   It has been done accordingly.
6) How to choses the chemical properties of concrete mix for max compressive strength and investigated specimens?
   Concrete mixing characteristics were determined after empirical experiments with the highest mechanical properties. This specification was obtained after an experimental test on about 15 samples.
7) The effect of the size added to the conclusion section.
   The residual compressive strength amount of the LWAC decreased depending on the increasing temperature. But, the residual strength properties of LWAC produced by expanded fine aggregate were higher than the concrete produced by coarse aggregates. The mixture containing natural aggregate completely disintegrated at 1000°C. However, mixtures with expanded clay aggregate were more resistant at 700 °C. This comment added to the conclusion of the revised paper.

EXAMINING THE STRENGTH OF LIGHTWEIGHT AGREGGATE FOAMED CONCRETE EXPOSED TO ELEVATED TEMPERATURES

ABSTRACT

This paper reports the results of an experimental tests to investigate the mechanical properties of six mixes of lightweight aggregate concrete (LWAC) exposed to high temperatures (200 to 700 ˚C). To this end; the first three mixes were considered as reference mixes consisting of cement, porcelanite as coarse aggregate, and fine porcelanite as a partial replacement and a total replacement of sand. As well, two percent of foam agent by weight of water was added to manufacture LWAFC. The testing results showed that the resistance of foamed concrete (FC) at elevated temperatures was better in terms of the proportional loss in strength than that of normal concrete. Furthermore, the mechanical properties of the LWAFC containing 50% and 100% of fine porcelanite aggregate had been less affected by high temperatures than those in the sanded LWAFC.

Keywords: Lightweight Concrete, Foam Concrete, Elevated Temperature, Thermal Conductivity, Porcelanite

INTRODUCTION

Foamed concrete shows excellent physical characteristics such as relatively high strength, low self-weight and acoustic insulation and superb thermal properties. Foamed concrete depends on its many characteristics for its different applications in building construction. These are some guidelines on production and processes to produce the best foamed concrete. Numerous studies have been conducted extensively on lots of natural lightweight aggregate in order to manufacture LWC [1-4] because the use of natural lightweight aggregate instead of ordinary ones can reduce the costs of such concrete. There are also different types of natural lightweight aggregate such as perlite, pumice, porcelanite, volcanic scoria, diatomite, etc.

Likewise, the cellular structure of lightweight aggregate (LWA) can makes it inherently insulating, and this factor can be assumed responsible for the high thermal insulation of LWAC. Also, this type of LWC is generally endowed with lower thermal expansion than normal weight concrete (NWC); therefore, it is more stable at elevated temperatures than other dense aggregate concrete types. This property, combined with better thermal insulation, can thus produce the inherent fire-resistance characteristic feature of the LWAC [5-7].

Moreover, heat exposure may be found in some industrial installations wherein concrete is used in places exposed to sustained elevated temperatures ranging from 100 to 1000°C as those utilized in foundations for blast furnaces and coke batteries, furnace walls and dampers, industrial chimneys, flues, kilns, as well as nuclear reactors [3].

Since concrete is known as a composition of different materials, its behaviour under elevated temperatures can largely depend on the constituents; in this respect, the aggregate type and the structure of the cement paste can have significant effects on thermal conductivity of concrete. The highly porous microstructure of the LWA also gives it low density and better insulation that can consequently make concrete produced with LWA exhibit lower thermal conductivity compared to the NWC. Therefore, lightweight aggregate foamed concrete (LWAFC) can provide more effective fire protection than other types of concrete as it is less liable to spalling and endowed with a higher thermal insulation [2].

In this regard, numerous studies have been carried out to investigate the properties of the LWC exposed to elevated temperatures using various types of LWA. There are also investigations dealing with the effects of high temperatures on chemical and mechanical properties of the LWC [1-4]; however, the impacts of high temperatures on chemical and mechanical properties of foamed concrete (FC) cannot be observed except in few research studies [9]. So, the present investigation was to examine the properties of FC and to make attempts to improve these properties using local and low-cost materials. In this study, compressive strength and density were also measured. Furthermore, the analytical study involved thermal conductivity analysis of the LWAFC. Because of the there is no study about on the effect of high temperature on mechanical properties of the LWAFC, also in this paper six mixes of LWAC produced to examine the effects of elevated temperatures (200 to 700 ˚C) on their residual mechanical properties.

Abbreviations

LWAC	Lightweight Aggregate Concrete
LWAFC	Lightweight Aggregate Foamed Concrete
NWC	Normal Weight Concrete
OPC	Ordinary Portland Cement
ASTM	American Society for Testing and Materials
LOI	Loss on Ignition
IQS	Iraqi Standards

SIGNIFICANCE OF THE STUDY

The present study focused on the use of FC made with porcelanite as coarse aggregate and as a partial and a total percentage replacement of fine aggregate. The primary scope of this study was to investigate the effect of elevated temperatures on the properties of the LWAFC.

EXPERIMENTAL INVESTIGATION

The effects of various test parameters on the properties of the LWAC and the LWAFC were investigated in this study. To this end, all mixes were exposed to different temperature levels and the period of exposure at the maximum temperature lasted two hours.

The investigation was based on using locally manufactured cement Type I (ordinary Portland cement: OPC) produced by Al Kubaisa Cement Factory, whose chemical and physical properties were illustrated in Table 1 and porcelanite crushed stone obtained from the north of Al-Rutba Town in Al-Anbar Governorate, Iraq. Table 2 also listed some important physical and chemical properties for coarse and fine porcelanite aggregate. Moreover, EUCO-type foaming agent was used in this study to produce the LWAFC with 2% foaming agent by weight of water [9]. Table 3 indicated the technical description of the foaming agent.

The coarse aggregate used was 10 mm in all mixes. Porcelanite, as a partial and a total replacement for local natural sand with a 2.61 fineness modulus, was also used as fine aggregate. Its gradation also lied in zone 3 and the grading test results were consistent with Iraqi Specification No.45/1984 as shown in Figures 1 and 2 indicating grading of fine and coarse aggregate used in this investigation. Potable water of Al-Risafa, Baghdad, was also used throughout this investigation for mixing and curing.

TEST PARAMETERS

The test parameters investigated in the present study were:

- Porcelanite as fine aggregate replacement, and a partial and a total replacement;

- Level of exposure temperatures, the specimens at an age of 60 days were heated in an electric furnace and four maximum temperature levels were selected (200, 300, 400, and 700˚C) and the period of exposure at the maximum temperature lasted two hours.

MIXTURE PROPORTIONS AND DETAILS

This investigation was carried out in three different series and the mix proportioning was calculated according to ACI 211-98 [10]. An extensive series of tests were also conducted to develop suitable LWAC and LWAFC reinforced with fiber classified into:

- Series I – MSP, MSPP, and MPP (mixture details were presented in Table 4)

- Series II – MSPF, MSPPF, and MPPF (mixture details were illustrated in Table 4)

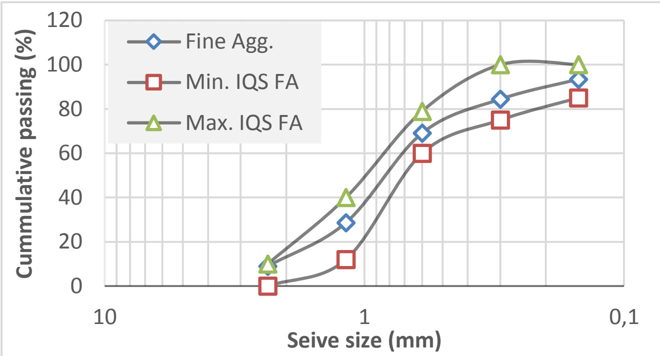


Figure 1. Particle size distribution of fine aggregate

Alumina, Al_2O_3	4.9	-
Iron oxide, Fe_2O_3	3.08	
Sulfate, SO_3	2.3	2.8% Max.
Loss on Ignition, (LOI)	1.5	4% Max.
Insoluble material	1.1	1.5% Max.
Lime Saturation Factor, (LSF)	0.937	(0.66-1.02)
Main compounds (Bogue's equation)		
C_3S	50.96	-
C_2S	21.77	-
C_3A	7.77	-
C_4AF	9.36	-
Physical properties		
Specific surface area (Blaine method), (m^2/kg)	304	230 m^2/kg lower limit
Setting time (vicate apparatus) Initial setting, hrs.: min Final setting, hrs.: min	2:05 3:60	Not less than 45 min Not more than 10 hrs
Compressive strength (MPa) For 3 days For 7 days	20.4 28.2	Not less than 15 MPa Not less than 23 MPa
Expansion by autoclave method	0.23%	Not more than 0.8 %

Table 2. Chemical and physical properties of fine and coarse porcelanite aggregate

Physical properties			
Property	**Coarse aggregate**	**Fine aggregate**	**Specification**
Specific gravity	1.55	1.68	ASTM C127-04
Absorption, %	39	42	ASTM C127-04
Dry loose unit weight, kg/m³	600	740	ASTM 29/C29M/02
Dry-rodded unit weight, kg/m³	685	860	ASTM 29/C29M/02
Aggregate crushing value, %	16		BS 812-part 110-1990

Chemical properties	
Oxides	% by Weight
SiO_2	69.86
CaO	10.57
MgO	6.90
SO_3	0.30
Al_2O_3	4.78
Fe_2O_3	2.09
TiO_2	0.18
L.O.I	4.25
Total	98.97

Table 3. Physical Properties of foaming

Appearance	Liquid
Color	Transparent
Specific gravity	1.01
Chloride content	Nil
Compatibility with cement	All types of Portland cement
Shelf life	Up to 2 years
Surface tension	41.9N/cm²

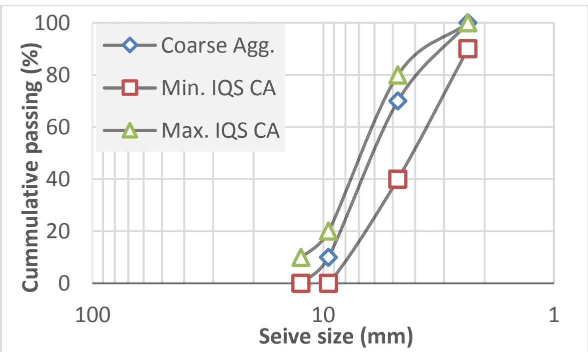


Figure 2. Particle size distribution of coarse aggregate

CONCRETE MIXING, TEST SPECIMENS, CURING, CONDITIONS, AND TESTING DETAILS

The mixing sequence was as follows: coarse aggregate and fine aggregate were added into the mixer and the mixing continued for 1 minute, then the required quantity of dry cement was added, and the mixing continued for 3 minutes in order to produce a good homogenous mix. Two thirds of the required quantity of water was then added to the dry materials, and the remaining water and the required quantity of foaming agent were added to the machine to make foam which was then added to the mix [9].

The slump of fresh concrete mixtures was determined as per ASTM C143. Sixty days of compression were then determined by crushed 100mm cubes as per B.S. 1881: part 120: 1983 and flexural strength was specified by crushed (400×200×50) mm flags as per IQS No.1107, 1988 Type C [11]. Moreover, three specimens were examined for each test and their mean values were reported. Two specimens (200×100×50) mm were then cast for each concrete mixture in order to check the thermal conductivity as per B.S. 874: 1973 [12].

HEATING PROCEDURE

For all the exposures, the specimens were slowly heated and cooled to allow the maximum exposure temperature to reach the centre of the specimens during heating and the rate of heating was such that it did not exceed 2°C/min to avoid steep thermal gradient [1, 13].

RESULTS AND DISCUSSIONS

Fresh Properties

Investigating the effect of foaming agent, Table 4 showed that the values of fresh properties (slump) of the LWAC varied from 120 to 160 mm. For the LWAFC, these values were in the range of 242 to 248 mm indicating that Series II of lower w/c (0.4) had larger slump compared to Series I. It was also observed that the addition of foaming agent had increased the workability due to the fact that cohesion had been improved by the use of foaming agent and these observations were in line with those reported by [4, 9].

Influence of Elevated Temperatures on LWAC and LWAFC

Loss of Weight

All the series exhibited smaller losses in weight with respect to exposure temperatures as plotted in Figures 3 and 4. The decrease in weight was not also more than 2% at 200ºC and 7% at 300ºC, for all mixes. This was due to the removal of the capillary and the adsorbed water from the cement paste. On the other hand, it became obvious that there was an increase in the loss of weight at a temperature above 300˚ C, and reduction of the weight ranging from a minimum of about 17% to a maximum of about 41% at 700˚C. This was due to further dehydration of the cement paste as a result of the decomposition of calcium hydroxide. It was also noticed that in Series I, the sanded-LWAC specimens (MSP and MSPP) showed a larger reduction in their weight compared to the MPP specimens containing fine porcelanite aggregate as a total replacement of natural sand. The results demonstrated that the MPP mixes were more thermally stable than the other mixes and the thermal stability of the concrete largely depended on the thermal stability of the aggregate (i.e. the thermal strain was dependent on aggregate used) [14].

Table 4. Mixture composition of all experiment series kg/m^3

Mixture ID*	Fine aggregate		Coarse porcelanite	w/c	Water	Foaming agent	Slump (mm)
	Sand	Porcelanite					
MSP	540	-	787	0.4	160	-	120
MSPP	270	153	787	0.43	172	-	155
MPP	-	313	787	0.45	180	-	160
MSPF	540	-	787	0.4	160	3.2	242
MSPPF	270	153	787	0.42	168	3.36	245
MPPF	-	313	787	0.45	180	3.6	248

*****Cement content in all mixes = 400 kg/m^3

** Aggregate in SSD condition wherein water quantities were adjusted before mixing

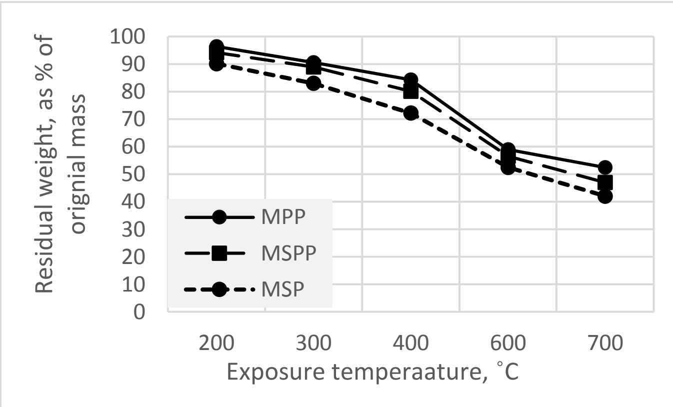


Figure 3. Residual weight as the percentage of original weight of LWAC

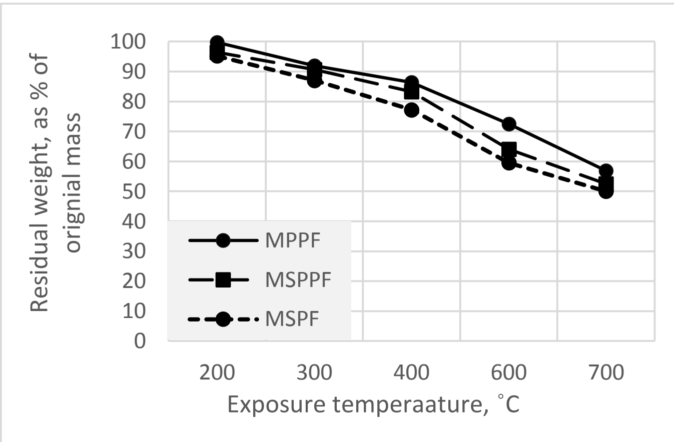


Figure 4. Residual weight as the percentage of original weight of LWAFC

Compressive Strength

The residual compressive strength of Series I and II decreased with the increase in temperature degrees as presented in Figures 5 and 6. The range of the properties of Series I and II concrete were also shown in Table 5. It should be noted that the residual compressive strength at 200˚C for Series I was approximately 70, 83, and 86% for MSP, MPPS, and MPP; respectively. As well, the residual compressive strength at 300˚C for Series I was about 62, 69, and 80% for MSP, MPPS, and MPP; respectively. At 400˚C, the residual strength was 38, 44, and 50% for MSP, MPPS, and MPP; respectively. At 600 ˚C, the residual strength was roughly 23, 34, and 41% for MSP, MPPS, and MPP; respectively. It should be added that the residual compressive strength at 700˚C for Series I was approximately 11, 20, and 23% for MSP, MPPS, and MPP; respectively. Furthermore, the residual strength of the MPP was reported higher compared to the MSP when subjected to different temperatures. The rate of loss of strength was also significantly at 700˚C especially for MSP compared to the others. The residual strength at 600˚C was equivalent to half of the residual strength at 300˚C. It should be noted that the dehydration of cement paste at high temperatures results in its gradual disintegration because the paste tends to shrink and aggregate may expand at high temperatures of above 600˚C; moreover, the bond between the aggregate and the paste is weakened resulting in a great reduction in strength as confirmed in test results [15,16]. The deterioration of strength at elevated temperatures for such concrete types could be attributed to the coursing of the pore structure and the increase in pore diameter [15, 16, 17].

The test results indicated each temperature range for Series II as plotted in Figure 6. The residual compressive strength at 200˚C for Series II was approximately 80, 87, and 91% for MSPF, MPPSF, and MPPF; respectively. As well, the residual compressive strength at 300˚C for Series II was approximately 69, 75, and 85% of MSPF, MPPSF, and MPPF; respectively. At 400˚C, the residual strength was 61, 63, and 69% for MSPF, MPPSF, and MPPF; respectively. At 600 ˚C, the residual strength was roughly 47, 49, and 50% for MSPF, MPPSF, and MPPF; respectively. The residual compressive strength at 700˚C for Series II was also about 40, 44, and 47% for MSPF, MPPSF, and MPPF; respectively.

Generally, the strength loss in Series II was lower compared to Series I when the temperature varied from 200 to 700˚C. For instance; at 700˚C, the residual strength was respectively 40, 44, and 47% of MSPF, MPPSF, and MPPF which were considered higher compared to those in

Series I. This was an indication of better performance of the LWAFC in retaining the strength at elevated temperatures compared to LWAC. This could be attributed to the less dense pore structure of Series II (compared to Series I) due to the presence of comparatively porous cement paste and the LWA (porcelanite).

At 700˚C, Series I and Series II specimens experienced considerable cracks as well as spalling. The color of specimens also turned pink. The specimens then demonstrated surface features when exposed to 600˚C and showed color changes as well as some edge cracks but not as severe as those exposed to 700˚C shown in Figure 7.

Series II could exhibit more resistance to elevated temperatures than Series I due to much less tendency to spalling and loss of less proportion of their original strength with the rise in temperature [18].

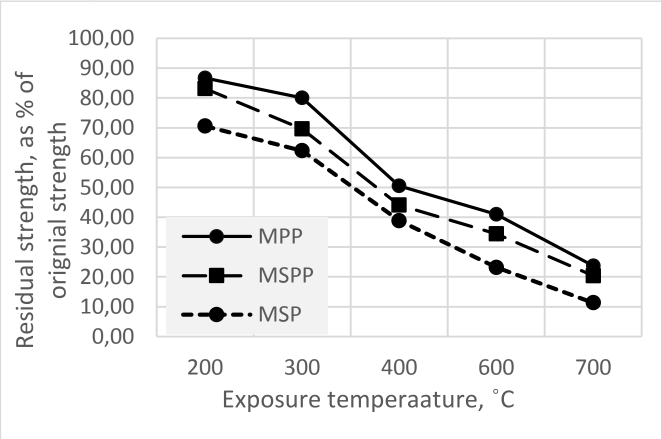


Figure 5. Residual strength as percentage of original strength of LWAC

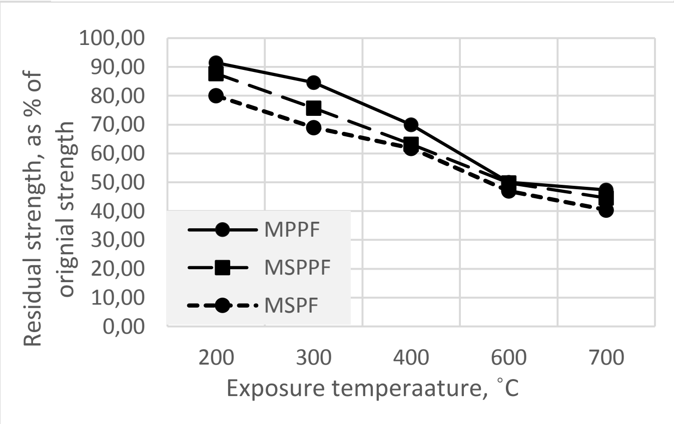


Figure 6. Residual strength as percentage of original strength for LWAFC

Figure 7. Concrete specimens after 2 hrs of elevated temperatures

Thermal Conductivity

The variations in the thermal conductivity of all series of specimens with respect to exposure temperature were plotted in Figure 8. The coefficient of thermal conductivity decreased when the air-filled pores increased since air is a very poor conductor of heat; thus, the results showed that the coefficient of thermal conductivity of Series II was lower compared to Series I. Also, the thermal test revealed a good indicator of the behavior of the LWAFC under elevated temperatures. Generally, the results showed that Series II mixes had more thermal stability compared to those in Series I. The thermal conductivity also dropped sharply for the sanded-LWAFC (MSP) between 300 and 700˚C, by approximately 35.2, 40.1, 40.3, 61.5, and 73.9% at 200, 300, 400, 600, and 700˚C; respectively, while the same mixes with the foaming agent could undergo a slight drop about 27.9, 31.6, 35.7, 53.5, and 64.2% at 200, 300, 400, 600, and 700˚C; respectively. The thermal stability of the concrete also largely depended on the thermal stability of the aggregate (i.e. the thermal strain was dependent on the aggregate used) [13]. This was firstly due to the cellular nature of porcelanite aggregate and secondly because of the mineral composition of this type of aggregate which consisted of approximately 65% mineral-type Opal-CT considered as amorphous siliceous mineral with low thermal conductivity compared to crystalline silica [19]. The results also showed that the addition of foaming agent could give better thermal insulation to the LWAC mixes at 25˚C. Simply, the requirement for resistance against elevated temperatures was based on thermal insulation.

Conclusion

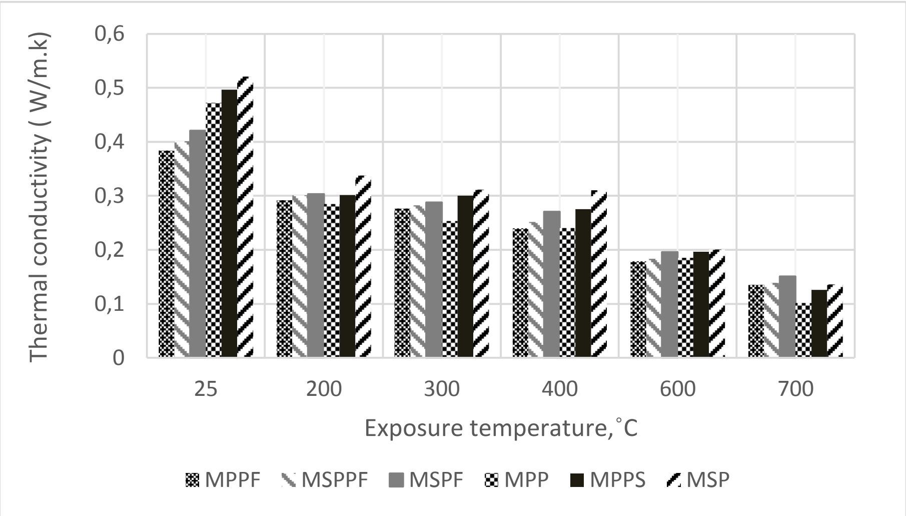
The following conclusions could be drawn from this study:

- The addition of foaming agent by 2% was beneficial in terms of improving the workability of the LWAC. The slump values of the LWAFC between 242 and 284 mm also showed satisfactory workability with no segregation or excessive bleeding specially for the MPPF mixture.
- The compressive strength and density decreased with the increase in the replacement of porcelanite with sand. The proportional loss in strength between normal concrete LWAFC containing 50% (MSPPF) and 100% fine porcelanite aggregate (MPPF) also showed a little loss in mechanical properties compared to the sanded-LWAFC (MSPF).
- The behavior of Series I mixtures under compressive strength was more sensitive to elevated temperatures than those of Series II.
- The residual compressive strength of Series II specimens was more than those in Series I especially when exposed to high temperatures; i.e. the residual strength was 69, 50, and 47% for the MPPF at 400˚C, 600 ˚C, and 700˚C; respectively.
- MSP specimens had a minimum residual strength in comparison to the other ones, especially at elevated temperatures, equal to 38, 23, and 11% at 400˚C, 600 ˚C, and 700˚C; respectively.

- The residual compressive strength amount of the LWAC decreased depending on the increasing temperature. But, the residual strength properties of LWAC produced by expanded fine aggregate were higher than the concrete produced by coarse aggregates. The mixture containing natural aggregate completely disintegrated at 700°C. However, mixtures with expanded clay aggregate were more resistant at 700 °C.

Table 5. Summary of mechanical properties

Mixture ID*	Density, kg/m^3						Compressive strength, MPa					
	Temperatures, ˚C						Temperatures, ˚C					
	25	200	300	400	600	700	25	200	300	400	600	700
MSP	1500	1431	1345	1265	884	786	19.4	16.8	15.5	10	8	5
MSPP	1457	1372	1297	1169	823	685	18.5	15.4	13	8	6.4	4
MPP	1280	1154	1063	924	672	538	15.8	11.2	10	6	3.6	2
MSPF	1390	1385	1277	1201	1007	790	13	12	11	9	6.5	6
MSPPF	1351	1302	1225	1126	864	709	10	8.7	7.5	6.3	4.9	4.5
MPPF	1210	1159	1053	934	720	606	9.4	7.5	6.5	5.8	4.4	3.7



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