

The Effect of Elevated Temperature on the Lightweight Concrete Produced by Expanded Clay Aggregate and Calcium Aluminate Cement

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Abstract: In this study, the influence of elevated temperature on the physical and mechanical properties of concrete produced by expanded clay aggregate and calcium aluminate cement (CAC) was investigated. For this purpose three different mixture were prepared. First mixture was produced by using ordinary Portland Cement (OPC) and natural aggregate. Second mixture was prepared by OPC and expanded clay aggregate. Third mixture was produced by using CAC and expanded clay aggregate. The water-cement (w/c) ratio used in the mixtures was set at 0.50. The concrete specimens were heated in an electric furnace up to 200, 400, 600, 800 and 1000 °C and kept at these temperatures for one hour. Two cooling regimes (slow and fast) were used. The residual compressive strength, weight loss, water absorption and porosity ratio and ultrasonic wave velocity values of the specimens were measured. The test results show that exposing to elevated temperatures adversely affected the mechanical and physical properties of the specimens containing OPC and natural aggregate. However, the lightweight concretes produced by expanded clay aggregate demonstrated better performance. Fast cooling (FC) method caused significant strength losses than slow cooling (SC) method.

Keywords: Elevated temperature, expanded clay aggregate, calcium aluminate cement, lightweight concrete, compressive strength

1. Introduction

One of the most important physical deterioration processes that influence the strength and durability of concrete structures is high temperature (Aydin, 2008; Huang et al., 2017). High temperature may cause permanent damage in the structures; consequently, the building which is exposed to high temperature may be out of service (Khoury and Majorana, 2003). Concrete is a fire resistant material because of its properties such as being a non-flammable material, is not important damaged for a certain period and doesn't remove toxic fumes in high temperature (Li and Ding, 2003). However, this durability is valid for a limited period and certain temperatures (Kızılkant and Yüzer, 2008). High temperature causes a decrease in compressive strength of concrete significantly. This effect changes depending on various factors. The factors that influence the strength of concrete upon heating are mainly grouped as material and environmental factors. Material factors such as

type of aggregate, properties of cement paste, the adhesion of aggregate and cement paste and thermal incompatibility between components of the composite influence the strength of concrete at high temperatures. On the other hand, environmental factors including heating rate, duration of exposure to maximum temperature, cooling rate, loading conditions and moisture regime, which are also important for the behavior of concrete composites at high temperatures (Khoury, 1992; Ahmed et al., 1992; Sarshar and Khoury, 1993; Chan et al., 2000; Cülfik and Özturan, 2002; Tanyıldızı and Coşkun, 2008).

The physical and chemical properties of concrete change after exposed to high temperatures. High temperatures, in general, cause deterioration in properties of concrete such as compressive strength, flexural strength, modulus of elasticity and bond with reinforcement (Lau and Anson, 2006). When concrete is exposed to high temperatures, the free water in the pores and some

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chemically bonded water in the hydrated cement paste are released and large amount of energy is consumed (Othuman and Wang, 2011; Jang et al., 2016; Mohammadhosseini and Yatim, 2017). Free water evaporates at around 100 °C and is completely removed at 120 °C. Above approximately 150 °C, the water chemically bound in hydrated calcium silicate begins to move away with a peak rate of loss at 270 °C (Hertz, 2005; Othuman and Wang, 2011; Al-Sibahy and Edwards, 2012). Because of the difference between the coefficients of thermal expansion of the cement paste and aggregate, thermal stresses are induced between the expanding aggregate and shrinking cement paste. The induced stress causes fractures on the interfacial bond between the aggregate and the surrounding cement paste this situation results in strength loss of concrete specimens (Cülfik and Özturan, 2010). The propagation of micro-cracks begins after 300 °C and mechanical strength and thermal conductivity decrease at this stage, with some associated expansion taking place (Hertz, 2005; Demirel and Keleştemur, 2010). Between 400 °C and 600 °C, complete desiccation occurs and crystals of calcium hydroxide decompose into their original components (calcium oxide and water). At this stage concrete becomes quite weak (Go et al., 2010). Above 600 °C, further decomposition of hydrated calcium silicate takes place and spalling is observed. The cement paste turns into a glassy phase above 1150 °C (Al-Sibahy and Edwards, 2012).

One of the most effective approaches to increase the duration of fire resistance is using lightweight concrete for producing structural elements. Since the lightweight aggregate is a product of high temperate sintering which results in more internal holes inside the aggregate, lightweight concrete has a better thermal stability, lower thermal conductivity and lower thermal expansion coefficient than normal weight concrete (Topçu, 1997; Go et al., 2010). Because of their high density and lower permeability normal weight concrete has a greater tendency toward explosive spalling than lightweight concrete at high temperatures (Al-Sibahy and Edwards, 2012).

The most common way to produce lightweight concrete is using lightweight aggregate. One of the lightweight aggregate which has high strength is expanded clay aggregate (Köksal et al., 2012; Ahn et al., 2016; Ahmmad et al., 2017). Expanded clays are spherically shaped beads with variable

granulometry, showing a vitrified morphology. The beads are fragile and hard with closed internal micro cavities that influence the thermal insulating properties.

Calcium aluminate cement (CAC) is versatile special cement advantageously used in numerous specific applications, such as manufacturing of monolithic refractories, foundries, furnaces and fireplaces, rapid repair mortars, ceramic adhesives and sealing materials (Scrivener et al., 1999; Öztürk, 2008; Neven, 2010). The main special properties of CAC are rapid strength development, good resistance to sulfates, enhanced resistance to abrasion and ability to withstand repeated heating up to high temperatures (Scrivener, 2003; Juenger et al., 2011). It develops about 80% of its ultimate strength after only 24 h of beginning of the hydration (Ewais et al., 2009). Due to the rapid hydration property, CAC is useful for low temperature applications (Fernandez-Carrasco et al., 2005). The most important feature of CAC is capability to withstand high temperatures up to 1600-2000 °C depending on the type and content of impurities in it (Girgis et al., 2000; Scrivener, 2003; Fernandez-Carrasco et al., 2005).

2. Materials

Ordinary Portland cement CEM I 42.5 R (OPC) conforming to TS EN 197/1 (2012) and Calcium aluminate cement (CAC) conforming to TS EN 14647 (2010) specifications were used as binder in the mixtures. The 28-day compressive strength of OPC according to TS EN 196-1 (2009) was 49.7 MPa. And the 24-hours compressive strength of CAC was 78 MPa. Physical properties and chemical oxide compositions of OPC and CAC are presented in Table 1 and Table 2, respectively.

Table 1. Physical properties of OPC and CAC

Cement type	Specific weight (g/cm ³)	Specific surface area (cm ² /g)	Setting times (min)	
			Initial	Final
OPC	3.10	3670	143	200
CAC	3.25	3100	235	255

Table 2. Chemical properties of OPC and CAC

Oxide (%)	OPC	CAC
SiO ₂	19.48	3.77
Al ₂ O ₃	5.06	40.27
Fe ₂ O ₃	2.47	16.68
CaO	62.46	36.40
MgO	2.94	0.62
SO ₃	3.60	0.02
K ₂ O	0.72	-
Na ₂ O	0.54	0.07
LOI	3.66	0.30

Natural aggregate and expanded clay aggregate were used in the mixture for experimental studies. Uncrushed, quartzitic natural sand with maximum

size of 4 mm and crushed basaltic coarse aggregate with maximum size of 8 mm in accordance with TS 706 EN 12620+A1 (2009) were used as natural aggregate. The specific weights of fine and coarse aggregates at saturated surface dry condition were 2.48 g/cm³ and 2.56 g/cm³, respectively. The water absorption values of fine and coarse aggregates were 4.1% and 1.7%, respectively. In addition, 780 lt 1/8 mm and 0/2 mm expanded clay aggregate which was supplied from Liapor was used to prepare one cubic meter of concrete mixture. The dry specific weight and water absorption values of expanded clay aggregate were 0.43 g/cm³ and 20.1% respectively. The grading of aggregates is presented in Table 3 with the standard specification.

Table 3. Aggregate grading with standard limits

Sieve size (mm)	Passed (%)				
	TS 706 EN 12620 + A1			Aggregate used	
	Lower limit	Medium limit	Upper limit	Natural	Expanded clay
16	100	100	100	100	100
11.2	98	99	100	100	100
8	85	92	99	97	98
4	62	75	88	65.5	73.3
2	40	56	72	48.5	42.5
1	23	39	55	30.8	25.5
0.5	13	26	38	16.1	16.7
0.25	7	15	22	9.0	12.9
0.125	3	8	12	5.5	6.5
0.63	1	3	5	2.1	3.2

Polycarboxylic ether based super plasticizer (SP) according to TS EN 934-2 (2011) was used to improve workability of the mixtures. The specific weight of super plasticizer was 1.142 g/cm³.

3. Mixture Properties and Testing Methods

Three mixtures were prepared for experimental studies. OPC and natural aggregate were used together in M1 mixture, OPC and expanded clay aggregate were used in M2 mixture and CAC and expanded clay aggregate were used in M3 mixture. M1 mixture which was considered as reference mixture was designed with according to absolute volume method given by TS 802 (2009). In M2 and M3 mixtures, expanded clay aggregates were pre-wetted, and then used in the mixtures. The water-cement (w/c) ratio used in mixtures was chosen as 0.50. Cement content was kept constant

for per cubic meter as 400 kg/m³. For each concrete mixture of a cubic meter, approximate concrete composition is presented in Table 4.

Table 4. Approximate concrete composition for a cubic meter (kg/m³)

Mixture	Cement		Natural aggregate		Expanded Clay		Water	SP
	OPC	CAC	Coarse Aggregate	Fine Aggregate	HD 0/2	HD 1/8 (5N)		
M1	400	-	562	1066	-	-	200	1,84
M2	400	-	-	-	355	600	200	4,88
M3	-	400	-	-	355	600	200	4,88

Cubic specimens with a 71 mm side were cast and fresh unit weights of the specimens were measured. They were de-molded after 24 hours and then cured in lime saturated water at 20±2 °C until the time of the compressive strength tests. In addition, the specimens which would be exposed to the elevated temperatures were cured in lime saturated water at 22±2 °C for two months. Afterwards they were cured in laboratory at 22±2 °C and 45±5 % relative humidity conditions for two months.

The six specimens were prepared for each mixture to perform compressive strength and ultrasonic wave velocity tests after elevated temperature. The specimens which were cured in laboratory for two months were placed in an electric furnace in which temperature was increased to 200, 400, 600, 800 and 1000 °C at a rate of 8 °C/min, and they were kept at desired temperatures for one hour. At the end of one hour the specimens were cooled in two regimes. Three specimens were left in the laboratory conditions for slow cooling (SC) in air and the other three specimens were left in the water for fast cooling (FC). After the cooling period, the compressive strength and ultrasonic wave velocity tests were carried out on the specimens. In addition, three unheated control specimens were used for comparison purpose.

The six specimens were used for the weight loss and water absorption and porosity ratio measurements. The curing conditions and the temperature values were similar to compressive strength tests. However, these specimens were dried at 105 °C before exposure to high temperatures due to lose of the moisture in the specimens completely.

The compressive strength of concrete specimens was measured according to TS EN 12390-3 (2010). Experiments were carried out at uniaxial compression instrument with a capacity of 3000 KN and loading rate was 0.5 MPa/s. The compressive strength tests were carried out on two

groups of specimens. The first group specimens were tested at 3, 7, 28, 90, 180 and 360 days. The second group specimens were tested after exposed to elevated temperatures. Three specimens were used at compressive strength measurement for each mixture and age. And the average of three measurements of specimens was presented and discussed in the study.

The ultrasonic non-destructive digital tester with a precision of 0.1 µs was used in order to measure ultrasonic wave velocity values of specimens which were exposed to the elevated temperatures. A transducer was used with a vibration frequency of 55 kHz. Sound transit times (t , µs) of concrete specimens were measured with through transmission technique according to ASTM C 597-09 (2009). Average of two readings was measured for each specimen and ultrasonic wave velocity values (V_s , km/s) were calculated.

The water absorption and porosity ratios of the specimens which were subjected to the high temperatures were measured according to TS 3624 (1981). In addition, the weights of the specimens before and after exposed to high temperatures were measured to determine the weight losses of the specimens. The test results were interpreted by comparing to each other.

4. Results and Discussion

4.1. Unit weight

The unit weights of fresh M1, M2 and M3 mixtures were 2320, 1510 and 1520 kg/m³, respectively. The air dry unit weights of all specimens decreased due to the evaporation of free water. The 90-day air dry unit weight values of the mixtures were 1920, 1150 and 1170 kg/m³ for M1, M2 and M3 mixtures, respectively. The average specific gravities at saturated surface dry condition of the M1, M2 and M3 mixtures were 2.0 g/cm³, 1.32 g/cm³ and 1.35 g/cm³, respectively. The dry unit weights of the M2 and M3 mixtures were

lower than 1850 kg/m³; in other words, they were within the limits of unit weight values specified at ACI 213R-14 (2014) for structural lightweight concrete.

4.2. Compressive strength

The compressive strength values of specimens are presented in Figure 1. The compressive strengths of all specimens increased depending on time. The 28-day compressive strength of M1 mixture produced by natural aggregate was 58.5 MPa. The compressive strength values of M2 and M3 mixtures produced by expanded clay aggregates were 31.1 and 28.8 MPa, respectively. Expanded clay aggregate caused the decrease of compressive strength values of the specimens. However, M2 and M3 mixtures were considered as structural lightweight concrete, since their 28-day compressive strength values were higher than 17 MPa (ACI 213R-14, 2014).

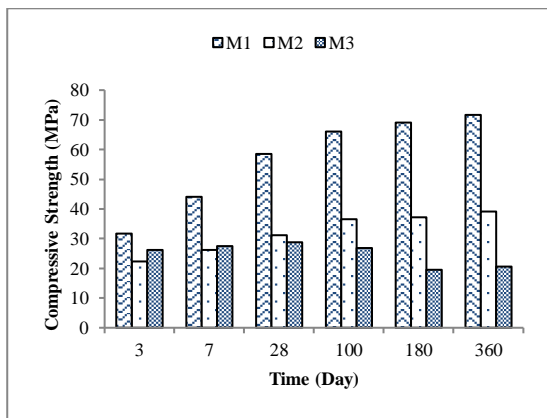


Figure 1. Compressive strengths of specimens (MPa)

It can be seen from Fig. 1 that the compressive strengths of M1 and M2 mixtures (containing OPC) increased rapidly up to 28 days. However, after 28 days the speed of compressive strength developments of these mixtures slowed down.

M3 mixture (containing CAC binder) exhibited more rapid initial strength development than the others. M3 mixture reached approximately 91% of its 28-day compressive strength at 3 days. One of the most important characteristics of CAC is rapid strength development. It develops about 80% of its ultimate strength after only 24 h of beginning of the hydration (Scrivener, 2003; Ewais et al., 2009)

However, the compressive strength values of M3 mixture showed a slight decrease after 28 days. It was stated in the literature that due to the temperature and humidity, deterioration is observed at CAC concretes depending on time. The hydrated products are reacted at about 25 °C and humidity conditions and decomposed. As a result of these reactions water releases and pores occurs in concrete. This situation may cause a reduction (about 40%) in strength (Postacıoğlu, 1986).

4.3. Residual compressive strength

The concrete specimens were exposed to the temperatures at 200, 400, 600, 800 and 1000 °C to determine the effect of elevated temperature on the compressive strength of the specimens. The residual compressive strengths of SC and FC concrete specimens are presented in Table 5 and Table 6, respectively. The relative reduction values at residual compressive strengths of mixtures compared to the original strengths before heating are given in parentheses.

Table 5. The residual compressive strengths of slow cooled (SC) mixtures (MPa)

Mixture	Compressive strengths of SC (MPa)					
	22 °C	200 °C	400 °C	600 °C	800 °C	1000°C
M1	79.1	66.5 (84%)	62.4 (79%)	48.1 (61%)	27.6 (35%)	*
M2	39.9	35.2 (88%)	32.2 (81%)	26.9 (67%)	18.5 (46%)	10.6 (27%)
M3	25.0	17.6 (70%)	14.1 (56%)	12.6 (50%)	10.6 (42%)	9.4 (38%)

*disintegrated

Table 6. The residual compressive strengths of fast cooled (FC) mixtures (MPa)

Mixture	Compressive strengths of FC (MPa)					
	22 °C	200 °C	400 °C	600 °C	800 °C	1000°C
M1	79.1	60.9 (77%)	51.5 (65%)	43.3 (55%)	22.7 (29%)	*
M2	39.9	33.6 (84%)	29.6 (74%)	23.2 (58%)	13.9 (35%)	9.2 (23%)
M3	25.0	16.2 (65%)	13.3 (53%)	11.7 (47%)	10.2 (41%)	9.3 (37%)

*disintegrated

The compressive strength values of M1, M2 and M3 mixtures were 79.1, 39.9 and 25.0 MPa, respectively at 22 °C. These values decreased depending on increasing temperature. At 600 °C, the residual strengths of slow cooled M1 and M2 mixtures were over 60% of the strengths measured at room temperature. M3 mixture showed approximately half of the strength of the mixture at 22 °C. When the temperature rised up to 800 and 1000 °C, the strength losses occurred in the mixtures increased significantly. The reason of this situation can be explain by decomposition of C-S-H gel (Lin et al., 1996; Xu et al., 2001). M1 mixture completely disintegrated at 1000 °C. It was stated in the literature that the residual strength of lightweight concrete after fire decreases from 100% to 40% as a result of increasing the temperature from 500 to 800 °C (Kong et al., 1983). In this investigation, the residual strengths of M2 and M3 mixtures (considered as lightweight concretes) at 800 °C were approximately 40% of initial strengths.

Cooling regimes significantly influences residual properties of concrete, such as compressive strength, splitting tensile strength, and fracture energy (Peng et al., 2008). The experimental results indicated that FC specimens exhibited similar behavior to SC specimens. However, the decreasing tendency at compressive strength was observed more significant at FC specimens than SC specimens for M1 and M2 mixtures. This result may be explained as follows. Free calcium hydroxide is turned into CaO (quick lime) by losing water over 400-500 °C. When CaO contacts with water, it rehydrates to form Ca(OH)₂ and this results in volume extension. (Sarshar and Khoury, 1993; Aydın, 2008). FC in water causes a denser pore structure in concrete than SC. This may be attributed to the re-hydration of the constituents resulting from decomposing of concrete at high temperatures (Khoury, 1992). In addition, due to the formation of crack which is occurred as a result of instantaneous temperatures changes at the FC method, residual compressive strength of FC

specimens is lower than SC specimens (Bilim, 2011).

The difference between the strength values of FC and SC specimens was not significant at M3 mixture. Because the hydration reaction of OPC results mainly in formation of C-S-H and Ca(OH)₂. Unlike OPC, there is no Ca(OH)₂ in hydration products of CAC (Kırca, 2006; Öztürk, 2008). Therefore, M3 mixture was less effected from FC methods than M1 and M2 mixtures.

4.4. Weight loss

The weight loss values of the specimens are presented in Table 7. In this investigation, the weights of the specimens decreased depending on increasing temperatures as similar to compressive strength values. The evaporation of free, hydrate and capillary water in the structure of the specimens exposed to the elevated temperatures causes to decrease in the unit weight of specimens (Topçu and Demir, 2007). In addition, the structural integrity of the specimens deteriorates as confirmed by the increase in weight reduction by increasing temperature (Demirel and Keleştemur, 2010; Andıç Çakır and Hızal, 2012).

Table 7. Weight loss of the specimens after exposure to elevated temperatures (%)

Mixture	200 °C		400 °C		600 °C		800 °C		1000°C	
	SC	FC	SC	FC	SC	FC	SC	FC	SC	FC
M1	0.15	0.59	1.47	0.71	2.56	1.06	3.98	2.25	*	
M2	0.13	0.40	1.74	0.55	3.45	0.96	4.11	1.30	6.60	4.69
M3	0.15	0.39	2.11	0.76	3.63	1.19	4.65	1.67	7.28	3.01

*disintegrated

The weight losses of FC specimens were higher than SC specimens at 200 °C. However, opposite situation was observed at 400-1000 °C. This result could be attributed that a small amount of water was remained in the pores of the specimens while the process of FC in water.

4.5. Water absorption and porosity ratios

Pore structure influences the strength of cement paste significantly, which is critical to the performance of the concrete as a whole. A coarsening of the pore size at elevated temperatures could result in a strength reduction (Khouri, 1992; Chan et al., 2000).

The water absorption and porosity ratios of the mixtures at elevated temperatures are presented in Table 8 and Table 9, respectively. In general, the water absorption ratios of M2 and M3 mixtures were higher than M1 mixture. It is stated in the literature that lightweight concrete absorbs more water than normal concrete and the water absorption ratio of lightweight concrete is between 12–22% (Akçaözöğlü et al., 2013). In this investigation the water absorption ratios of the M1, M2 and M3 mixtures at room temperature were 5.51%, 13.6% and 13.4%, respectively. The water absorption values of M2 and M3 mixtures were found to be within the water absorption limits of lightweight concrete.

Table 8. Water absorption ratios of the specimens after exposure to elevated temperatures (%)

Mixture	22 °C	200 °C		400 °C		600 °C		800 °C		1000°C	
		SC	FC	SC	FC	SC	FC	SC	FC	SC	FC
M1	5.51	6.1	6.2	6.2	6.6	8.8	7.0	10.1	8.1	*	
M2	13.6	13.6	13.9	14.7	15.1	18.8	16.0	20.8	17.6	19.9	19.8
M3	13.4	13.5	13.4	14.8	14.9	19.9	16.0	20.9	17.1	21.0	16.9

*disintegrated

Table 9. Porosity ratios of the specimens after exposure to elevated temperatures (%)

Mixture	22 °C	200 °C		400 °C		600 °C		800 °C		1000°C	
		SC	FC	SC	FC	SC	FC	SC	FC	SC	FC
M1	11.0	12.1	12.8	13.2	13.9	19.3	16.4	22.6	18.9	*	
M2	17.8	18.9	19.1	20.0	19.8	27.0	24.4	32.4	28.2	39.9	38.5
M3	26.8	27.6	27.8	30.4	28.3	33.8	30.0	36.0	33.9	39.3	35.3

*disintegrated

The water absorption ratios of the mixtures increased depending on increasing temperature. The increasing tendency of M1 mixture was more significant than M2 and M3 mixtures. This situation was parallel to porosity ratios of the mixtures. Porosity ratios of the mixtures increased

with an increase in temperature because of the processes of the decomposition of hydration products. It is stated in the literature that cement gel begins to dehydrate at approximately 180 °C and Ca(OH)₂ in cement paste decomposes at approximately 500 °C, and so on (Chan et al.,

2000). In general water absorption ratios of SC and FC mixtures were close to each other and similar situation was observed at porosity values of the specimens.

4.6. Ultrasonic pulse velocity (UPV)

UPV propagation speed in a material depends on the porosity of that material; therefore, it depends on the density and elastic properties (Topçu, 2006). While the compactness and density of concrete decreases, the UPV and strength of concrete decreases together.

The effect of elevated temperature on the porosity of specimens was evaluated by ultrasound measurements carried out in the research. The

effects of elevated temperatures over the range of 22 °C-1000 °C on the UPV of the mixtures are presented in Table 10. The UPV values of expanded clay aggregate specimens (M2 and M3) were lower than M1 at 22 °C. This situation was parallel to unit weight values of the mixtures. Using expanded clay aggregate in the specimens caused to reduction at unit weights due to the more porous structure, therefore UPV of these specimens decreased. This situation was observed as similar at 200 °C, 400 °C and 600 °C. However, UPV values of M2 and M3 mixtures were higher than M1 mixture at 800 °C. Because M1 mixture produced with natural aggregate was more affected from high temperature than M2 and M3 mixtures.

Table 10. UPV of the specimens after exposure to elevated temperatures (km/s)

Mixture	22 °C	200 °C		400 °C		600 °C		800 °C		1000°C	
		SC	FC	SC	FC	SC	FC	SC	FC	SC	FC
M1	4.56	4.44	4.64	3.66	4.06	2.34	3.77	1.27	2.39	*	
M2	3.59	3.42	3.57	3.13	3.36	2.31	3.34	1.97	2.73	1.67	1.81
M3	3.42	3.04	3.13	2.56	2.69	2.19	2.53	1.94	2.31	1.91	2.15

*disintegrated

Neville and Brooks (1987) reported that the UPV of a good quality concrete should be between 4.1-4.7 km/s for traditional concretes. The UPV value measured at room temperature of M1 mixture was between these values (4.56 km/s). Since M2 and M3 mixtures were considered as lightweight concrete, their UPV values were lower than these values, however their values were appropriate grades (3.59 and 3.42 km/s, respectively).

Exposing elevated temperatures adversely affected the mixtures. The UPV values of the specimens decreased depending on increase in temperature. Increasing temperature caused increasing pore structures of the specimens and evaporating the water in their structure caused weight loss and additional porous structures. This situation caused to decrease ultrasonic wave velocity values of the mixtures (Topçu and Demir, 2007; Demirel and Keleştemur, 2010). The UPV values of the FC specimens were higher than SC specimens at all temperatures. It is thought that a small amount of water was remained in the pores of the specimens while the process of FC in water.

In this investigation, a linear relationship was observed between UPV and porosity ratios of specimens at all temperatures (Fig 2-3). The correlation coefficients of relationships for SC and FC specimens were over 0.89 and 0.82, respectively. While the porosity ratios of specimens increased, the UPV of specimens decreased.

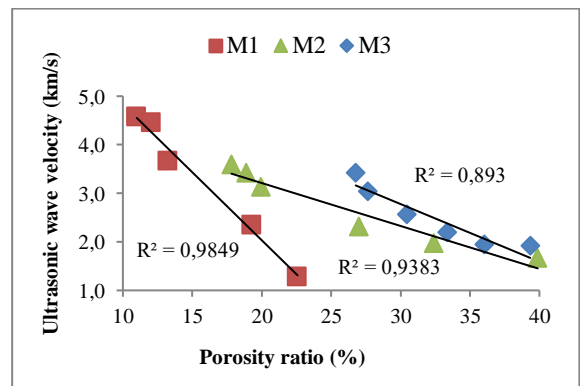


Figure 2. The relationship between the UPV and porosity ratios of SC specimens

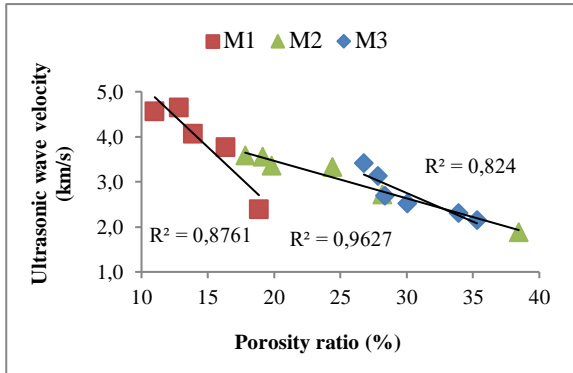


Figure 3. The relationship between the UPV and porosity ratios of FC specimens

5. Conclusions

This paper presents an experimental study on the effect of elevated temperatures on the lightweight concrete produced by expanded clay aggregate and calcium aluminate cement. The following conclusions can be drawn from the results of the current study:

- The concrete specimens produced with expanded clay aggregate in this investigation were considered as structural lightweight concrete in terms of unit weight and strength properties.
- The residual compressive strength values of the mixtures decreased depending on increasing temperature. Nevertheless, the residual strength properties of mixtures produced by expanded clay aggregate were higher than the concrete produced by natural aggregates. The mixture containing natural aggregate completely disintegrated at 1000 °C. However, mixtures with expanded clay aggregate were more resistant at 1000 °C.
- Fast cooling method resulted in more strength loss when compared to slow cooling method. CAC mixtures were not affected by cooling regime as much as OPC mixtures.
- The weights and the UPV values of specimens decreased depending on increasing temperatures.
- When the mixtures exposed the elevated temperatures their water absorption and porosity ratios increased, because of the processes of the decomposition of hydration products.
- In this investigation, a linear relationship was observed between ultrasonic wave velocity values and porosity ratios of the specimens.

- Conclusively, the mixtures produced by expanded clay aggregate and CAC were found to be able to retain their properties better at elevated temperatures.

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References

- ACI Committee 213R-14. (2014). Guide for structural lightweight aggregate concrete. Manual of Concrete Practice. American Concrete Institute. Michigan, USA.
- Ahmed, A.E., Al-Shaikh, A.H., Arafat, T. I. (1992). Residual compressive and bond strength of limestone aggregate concrete subjected to elevated temperatures. Magazine of Concrete Research, 44, 117-125.
- Ahmmad, R., Alengaram, U.J., Jumaat, M.Z., Sulong, N.H.R., Yusuf, M.O., Rehman, M. A. (2017). Feasibility study on the use of high volume palm oil clinker waste in environmental friendly lightweight concrete. Construction and Building Materials, 135, 94-103.
- Ahn, Y.B., Jang, J.G., Lee, H.K. (2016). Mechanical properties of lightweight concrete made with coal ashes after exposure to elevated temperatures. Cement and Concrete Composites, 72, 27-38.
- Akçaözöğlü, S., Akçaözöğlü, K., Atiş, C.D. (2013). Thermal conductivity, compressive strength and ultrasonic wave velocity of cementitious composite containing waste PET lightweight aggregate (WPLA). Composites Part B: Engineering, 45(1), 721-726.
- Al-Sibahy, A., Edwards, R. (2012). Thermal behaviour of novel lightweight concrete at ambient and elevated temperatures: Experimental, modelling and parametric studies. Construction and Building Materials, 31, 174-187.
- Andıç Çakır, Ö., Hızal, S. (2012). Influence of elevated temperatures on the mechanical properties and microstructure of self-

- consolidating lightweight aggregate concrete. *Construction and Building Materials*, 34, 575-583.
- ASTM C 597-09. (2009). Standard test method for pulse velocity through concrete. American Society for Testing and Materials. USA.
- Aydın, S. (2008). Development of a high-temperature-resistant mortar by using slag and pumice. *Fire Safety Journal*, 43, 610-617.
- Bilim, C. (2011). Properties of cement mortars containing clinoptilolite as a supplementary cementitious material. *Construction and Building Materials*, 25, 3175-3180.
- Chan, S.Y.N., Luo, X., Sun, W. (2000). Compressive strength and pore structure of high-performance concrete after exposure to high temperature up to 800 °C. *Cement and Concrete Research*, 30(2), 247-251.
- Chan, S.Y.N., Luo, X., Sun, W. (2000). Effect of high temperature and cooling regimes on the compressive strength and pore properties of high performance concrete. *Construction and Building Materials*, 14, 261-266.
- Cülfik, M.S., Özturan, T. (2002). Effect of elevated temperatures on the residual mechanical properties of high-performance mortar. *Cement and Concrete Research*, 32, 809-816.
- Cülfik, M.S., Özturan, T. (2010). Mechanical properties of normal and high strength concretes subjected to high temperatures and using image analysis to detect bond deteriorations. *Construction and Building Materials*, 24, 1486-1493.
- Demirel, B., Keleştemur, O. (2010). Effect of elevated temperature on the mechanical properties of concrete produced with finely ground pumice and silica fume. *Fire Safety Journal*, 45, 385-391, 2010.
- Ewais, E. M. M., Khalil, N. M., Amin, M. S., Ahmed, Y. M. Z., Barakat, M. A. (2009). Utilization of aluminum sludge and aluminum slag (dross) for the manufacture of calcium aluminate cement. *Ceramics International*, 35(8), 3381-3388.
- Fernandez-Carrasco, L., Puertas, P., Blanco-Varela, M.T., Vazquez, T., Rius, J. (2005). Synthesis and crystal structure solution of potassium dawsonite: An intermediate compound in the alkaline hydrolysis of calcium aluminate cements. *Cement and Concrete Research*, 35, 641-646.
- Girgis, L.G., El-Hemaly, S.A.S., Halil, N.M. (2000). Preparation and characterization of some improved high-alumina cement compositions. *Tile & Brick International*, 16(4), 250-256.
- Go, C.G., Tang, J-R., Chi, J.H., Chen, C.T., Huang, Y.L. (2010). Fire-resistance property of reinforced lightweight aggregate concrete wall. *Construction and Building Materials*, 30, 725-733.
- Hertz, K.D. (2005). Concrete strength for fire safety design. *Magazine of Concrete Research*. 57(8). 445-453.
- Huang, Z., Liew, J.Y.R., Li, W. (2017). Evaluation of compressive behavior of ultra-lightweight cement composite after elevated temperature exposure. *Construction and Building Materials*, 148, 579-589.
- Jang, H.S., So, H.S., So, S. (2016). The properties of reactive powder concrete using PP fiber and pozzolanic materials at elevated temperature. *Journal of Building Engineering*, 8, 225-230.
- Juenger, M.C.G, Winnefeld, F., Provis, J.L., Ideker, J.H. (2011). Advances in alternative cementitious binders. *Cement and Concrete Research*, 41, 1232-1243.
- Khoury, G.A. (1992). Compressive strength of concrete at high temperatures: a reassessment. *Magazine of Concrete Research*, 44(161), 291-309.
- Khoury, G.A., Majorana, C. (2003). Effect of heat on concrete. *International Centre for Mechanical Sciences*. Udine, Italy.
- Kırca, Ö. (2006). Temperature effect on calcium aluminate cement based composite binders [Ph.D. thesis]. Middle East Technical University, Ankara, Turkey.
- Kızılkant, A.B., Yüzer, N. (2008). Compressive strength-color change relationship in mortars subjected to high temperatures. *Chamber of Civil Engineers Technical Journal*, 289, 4381-4392.
- Köksal, F., Gencil, O., Brostow, W., Hagg Lobland, H.E. (2012). Effect of high

- temperature on mechanical and physical properties of lightweight cement based refractory including expanded vermiculite. *Materials Research Innovations*, 16(1), 7-13.
- Kong, F.K., Evans, R.H., Cohen, E., Roll, F. (1983). *Handbook of structural concrete*. Pitman Books Limited, London, England.
- Lau, A., Anson, M. (2006). Effect of high temperatures on high performance steel fibre reinforced concrete,” *Cement and Concrete Research*, vol. 36, pp. 1698-1707, 2006.
- Li, Z., Ding, Z. (2003). Property improvement of portland cement by incorporating with metakaolin and slag. *Cement and Concrete Research*, 33(4), 579-584.
- Lin, W.M., Lin, T.D., Powers-Couche, L.J. (1996). Microstructures of fire-damaged concrete. *ACI Material Journal*, 93(3), 199-205.
- Mohammadhosseini, H., Yatim, J.M. (2017). Microstructure and residual properties of green concrete composites incorporating waste carpet fibers and palm oil fuel ash at elevated temperatures. *Journal of Cleaner Production*, 144, 8-21.
- Neven, U. (2010). Kinetic modeling of calcium aluminate cement hydration. *Chemical Engineering Science*, 65, 5605-5614.
- Neville, A.M., Brooks, J.J. (1987). *Concrete technology*. Longman Group UK Limited, USA.
- Othuman, M.A., Wang, Y.C. (2011). Elevated-temperature thermal properties of lightweight foamed concrete. *Construction and Building Materials*, 25, 705-716.
- Öztürk, H. (2008). Thermal resistance of calcium aluminate cement and usage as a monolithic refractory material [M.Sc. thesis]. Erciyes University, Kayseri, Turkey.
- Peng, G.F., Bian, S.H., Guo, Z.Q., Zhao, J., Peng, X.L., Jiang, Y.C. (2008). Effect of thermal shock due to rapid cooling on residual mechanical properties of fiber concrete exposed to high temperatures. *Construction and Building Materials*, 22, 948-955.
- Postacıoğlu, B. (1986). *Concrete, Volume 1: Binding Materials*. Matbaa Teknisyenleri Press. İstanbul, Turkey.
- Sarshar, R., Khoury, G.A. (1993). Material and environmental factors influencing the compressive strength of unsealed cement paste and concrete at high temperatures. *Magazine of Concrete Research*, 45(162), 51-61.
- Scrivener, K.L. (2003). Calcium aluminate cements, *Advanced Concrete Technology: Constituent Materials*. In: Newman, J.B., Choo, B.S. (Ed.). Vol. 2, Elsevier Butterworth-Heinemann.
- Scrivener, K.L., Cabiron, J.L., Letourneux, R. (1999). High-performance concretes from calcium aluminate cements. *Cement and Concrete Research*, 29, 1215-1223.
- Tanyıldızı, H., Coşkun, A. (2008). Performance of lightweight concrete with silica fume after high temperature. *Construction and Building Materials*, 22, 2124-2129.
- Topçu, İ.B. (1997). Semi lightweight concretes produced by volcanic slags. *Cement and Concrete Research*, 27(1), 15-21.
- Topçu, İ.B. (2006). *Concrete technology*. Uğur Press, Eskişehir, Turkey.
- Topçu, İ.B., Demir, A. (2007). The effect of high temperature application time on the mortar properties. 7. National Concrete Congress, İstanbul.
- TS 3624. (1981). Test method for determination the specific gravity the absorption water and the void ratio in hardened concrete. Turkish Standard Institution. Ankara, Turkey.
- TS 706 EN 12620+A1. (2009). Aggregates for concrete, Turkish Standard Institution. Ankara, Turkey.
- TS 802. (2009). Design concrete mixes. Turkish Standard Institution. Ankara, Turkey, 2009.
- TS EN 12390-3. (2010). Testing hardened concrete - Part 3: Compressive strength of test specimens. Turkish Standard Institution. Ankara, Turkey.
- TS EN 14647. (2010). Calcium aluminate cement-Composition, specifications and conformity criteria. Turkish Standard Institution. Ankara, Turkey.
- TS EN 196-1. (2009). Methods of testing cement - Part 1: Determination of strength. Turkish Standard Institution. Ankara, Turkey, 2009.

- TS EN 197-1. (2012). Cement - Part 1: Composition, specification and conformity criteria for common cements. Turkish Standard Institution. Ankara, Turkey.
- TS EN 934-2. (2011). Admixtures for concrete, mortar and grout - Part 2: Concrete admixtures-Definitions, requirements, conformity, marking and labeling. Turkish Standard Institution. Ankara, Turkey.
- Xu, X., Wong, Y.L., Poon, C.S., Anson, M. (2001). Impact of high temperature on PFA concrete. Cement and Concrete Research, 31, 1065-1073.