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Determination of Mechanical Properties of the Concrete Affected by High Temperature by Destructive and Non-Destructive Test Methods

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Abstract: In this study, the effects of the elevated temperature on concrete specimens prepared with different aggregate types were investigated. For this purpose, 4 different series were prepared by using CEM I 42,5 (N) type Portland Cement and four different types of aggregates (basaltic crushed aggregate, stream aggregate, limestone and pumice as lightweight aggregate). 100 mm and 150 mm cube concrete samples were prepared for each series. When reached the specified curing age, prepared each concrete specimen was taken from the curing pool and exposed to high temperatures of 300 ºC, 600 ºC and 900 ºC respectively. Control specimens of each series were stored at room temperature. The compressive strengths, ultrasonic pulse velocity and the adherence strength of the concrete samples exposed to these temperatures were examined. At the end of this study, the compressive strengths of the series exposed to high temperature are compared. It is observed that the series which is produced with basaltic crushed aggregate is least affected and the series which is produced with lightweight aggregate is the most affected from the elevated temperature. Pull-out tests were carried out to the all prepared series and it was found that the adherence strength between the concrete and the reinforcement decreased as the temperature increased.

Key words: High temperature, adherence strength, pull-out, ultrasonic pulse velocity, concrete.

Yüksek Sıcaklıktan Etkilenen Betonun Mekanik Özelliklerinin Tahribatlı ve Tahribatsız Muayene Yöntemleri ile Belirlenmesi

Öz: Bu çalışmada, yüksek sıcaklıkların farklı agrega tipleri ile hazırlanan beton örnekler üzerindeki etkileri araştırılmıştır. Bu amaçla, CEM I 42.5 (N) tipi Portland Çimentosu ve dört farklı tipte agrega (bazaltik agrega, dere agregası, kireçtaşı ve hafif agrega olarak pomza) kullanılarak 4 farklı seri hazırlanmıştır. Her seri için 100 mm ve 150 mm küp beton örnekleri hazırlanmıştır. Belirtilen kürlenme yaşına geldiğinde, hazırlanan her bir örnek kürleme havuzundan alınmış ve sırasıyla 300ºC, 600 ºC ve 900 ºC yüksek sıcaklıklara maruz bırakılmıştır. Her serinin kontrol örnekleri ise oda sıcaklığında bekletilmiştir. Basınç dayanımı, ultrasonik ses hızı ve bu sıcaklıklara maruz kalan beton numunelerin yapışma dayanımı incelenmiştir. Bu çalışmanın sonunda, yüksek sıcaklığa maruz kalan serilerin basınç dayanımları karşılaştırılmıştır. Bazaltik agrega ile üretilen beton serilerinin yüksek sıcaklıktan az etkilendiği buna karşın hafif agrega (pomza) ile üretilen beton serilerinin yüksek sıcaklıktan çok daha fazla etkilendiği görülmüştür. Hazırlanan tüm beton serilere çekip-çıkarma (pull-out) testi yapılmış ve sıcaklık arttıkça beton ile donatı arasındaki yapışma kuvvetinin azaldığı saptanmıştır.

Anahtar kelimeler: Yüksek sıcaklık, aderans dayanımı, çekip-çıkarma, ultrasonik ses hızı, beton.

1. Introduction

Fire hazards cause extensive damage to structures built without sufficient resistance to high temperatures. Therefore, it is very important to build structures resistant to high temperatures. It is only possible to provide resistance to high temperatures with the use of structural material resistant to high temperature. Concrete is known to be the most commonly preferred structural material for construction operations. Reasons such as abundance of the concrete raw material in nature, ease of giving shape to it, its extended life cycle, and its convenience in terms of its strength and cost-effectiveness make concrete an indispensible building material. With the rapidly increasing population and advancements in the construction technologies, the importance of this material ever increases as it is commonly used in structures such as residences, factories, bridges, dams, roads, etc.

Concrete is a structural material, a mix of cement, aggregates, water along with additives and is the final form of cement which is initially hydrated and in a plastic-like concentration- after setting[1]. Properties of the

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materials used to produce concrete and their ratios affect the quality and performance of concrete [2,3]. Each one of the materials used has an impact on the concrete. It is known that aggregates are one of the main elements influencing the properties of concrete as constituent materials. The strength of concrete produced using different aggregates are not the same under high temperatures [4, 5]. This can be accounted for the mineral content of the aggregates. When considered as a whole, the components of concrete are known to have different thermal expansion coefficients. For this reason, temperature change in concrete will lead to different volumetric changes in its constituents which will lead to the formation of cracks and therefore, reduced concrete strength. This can be referred to as "thermal incompatibility of concrete components" [6, 7].

According to the research, high temperatures affect the durability of a structure and cause significant damage. Such an effect may cause permanent damage in the structure which may even result in material and immaterial damages [8].

As an example, the fires in the Great Belt Tunnel and Channel Tunnel in 1994 and 1996, respectively, led to explosions and destruction of the concrete profile due to high temperature and the fire building caught after the planes hit WTC in 9/11 claimed many lives in New York, USA. As it is clear from these examples, the thermal resistance of structural material is of utmost importance [9,10,11].

Concrete may explode under high temperatures. Such an explosion leads to or triggers other threats in addition to the fire hazard itself. Research attempted to estimate the behavior of the structural material during and after a fire hazard in terms of its structural safety and its integrity [12]. Previous studies often focused on the effects of high temperature on the "normal-strength concrete" [13]. However, modern structures of our time use "high-performance and high-strength concrete" with the addition of chemicals and minerals designed for industrial structures, tunnels or custom structures. The reason behind this preference is the economical, architectural and structural advantages such material has to offer. High-strength concrete is advantageous when compared to normal-strength concrete. Provision of appropriate fire safety measures is a necessary aspect of any construction design. The concrete used needs to be identified for its behavior under the effects of high temperature. As the porosity of high-strength concrete is lower in comparison and as it has a more compact structure, the performance of such concrete under the effect of high temperature is poor when compared to normal-strength concrete [14].

This study explores the effects of high temperature on the mechanical properties of concrete produced using different types of aggregates. For this purpose, properties of different types of fresh and hardened concrete produced using four types of aggregates were investigated using destructive and nondestructive methods.

2. 2. Materıals and Methods

2.1. Materials

2.1.1.Aggregate

A total number of four different types of aggregates, namely, basaltic crushed stone, stream aggregate, limestone, and natural aggregate, were used in the experimental study. Fine and coarse aggregate were used the same type raw material in the each mix design. Physical properties of the aggregates are shown in Table 1.

Table 1. Physical properties of the aggregates subjected to the test.

Aggregate Type	Specific Gravity (kg/dm^3)	Water Absorption (%)
Basaltic Crushed Stone	2,70	1,12
Natural (stream)	2,79	0,93
Pumice	1,91	22,33
Limestone	2,66	1,33

The results of the sieve analysis for natural (stream) aggregate, pumice, limestone and basaltic crushed stone aggregate are shown in Figure 1. In this study, aggregate D max is taken as 16 mm (Figure 1). Fine and coarse aggregate were proportions of 0-4 and 4-16 for each concrete.

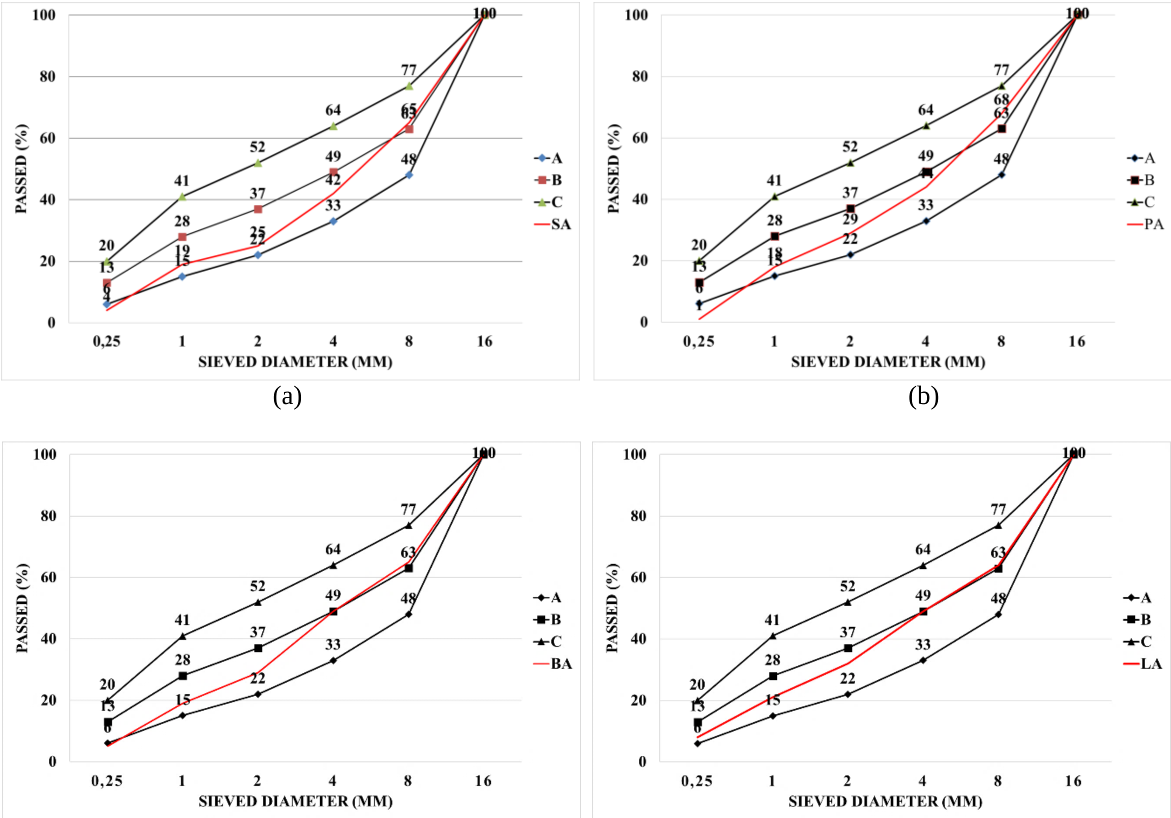

Figure 1: Aggregate granulometry: (a) Stream (Natural) Aggregate (SA); (b) Pumice (PA); (c) Basaltic Crushed Stone (BA); (d) Limestone (LA)

2.1.2. Cement

The type of cement used in the experiments was CEM I 42,5 N cement obtained from the Elazig Cement Factory. Dosage was constant in this study and it was defined as 400 kg/m^3. Physical and mechanical properties and chemical composition of the cement are shown in Table 2.

Table 2. Physical -mechanical properties and chemical composition of the cement

CEM I			
Chemical composition (%)		**Physical and mechanical properties**	
CaO	62,94	Specific gravity (kg/dm^3)	3,07
SiO_2	21,12		
Al_2O_3	5,62	Specific surface (cm^2/g)	3382
Fe_2O_3	3,24		
MgO	2,73		
SO_3	1,79	Compressive strength at 28th day (MPa)	51,7
Loss on ignition	1,78		

2.1.3. Mixing water

Mains water provided for the city was used as the mixing water in accordance with the TS EN 1008 standard for the concrete mix obtained.

2.2. Methods

Coding and definition of each one of the four series are shown in Table 3. Produced in accordance with this table and placed in casts of 100x100x100 mm and 150x150x150 mm (Figure 2) in size, concrete samples were then removed from casts and placed into a curing tanks which is saturated with lime at 23±2 °C to be taken out at the end of the specified curing time. Fresh concrete tests and destructive and nondestructive hardened concrete tests were performed on the samples as per the standards.

Table 3. Definitions and codes of concrete samples

Sample code	Definition of the sample	Aggregate type	Sample size (mm)
NC-1	100 mm^3 concrete sample with natural aggregate	Natural (Stream) aggregate	100x100x100
NC-2	150 mm^3 concrete sample with natural aggregate		150x150x150
PC-1	100 mm^3 concrete sample with pumice aggregate	Pumice aggregate	100x100x100
PC-2	150 mm^3 concrete sample with pumice aggregate		150x150x150
BC-1	100 mm^3 concrete sample with crushed stone aggregate	Basaltic crushed stone	100x100x100
BC-2	150 mm^3 concrete sample with crushed stone aggregate		150x150x150
LC-1	100 mm^3 concrete sample with limestone aggregate	Limestone aggregate	100x100x100
LC-2	150 mm^3 concrete sample with limestone aggregate		150x150x150

Figure 2. Cubic concrete samples produced using four different types of aggregates in two sizes (100x100x100 mm & 150x150x150 mm)

Slump test was conducted on the concrete samples in order to test the placeability of concrete before casting the concrete. Slump test was conducted in accordance with the TS EN 12350-5 standard in order to obtain information on the placeability of fresh concrete. In this study, flow diameter range of 420-480 mm was taken for the F3 class available in Table 4.

Table 4: Slump test class table

Class	Flow diameter (mm)	Tolerance
F1	< 340	+ 30
F2	350 - 410	
F3	420 - 480	
F4	490 - 550	
F5	560 - 620	
F6	>630	

Temperature tests were conducted only for samples cured for 28 days. Samples were subjected to high temperatures of 300 ºC, 600 ºC and 900 ºC [11] using a Protherm HLF 150 lab type furnace with a capacity of 1200 ºC and a heating speed of 6 ºC/min located in the Construction Lab of Fırat University. Baradan et al. (2002) reported that the strength of concrete is not affected by temperatures below 250°C. Therefore, the first test temperature was selected as 300°C which was then increased by 300°C for other tests. Having exposed to high temperatures, samples were then kept in a drying oven at 100±5 ºC until they reached saturated surface dry condition before they were treated in the stove. The furnace was set to automatically turn off after 1 hour having provided the specific testing temperature and the samples were then stored to cool down at room temperature. All the samples were subjected to destructive and/or nondestructive compressive strength tests and the data obtained was compared with that of the samples treated under room temperature (18-22°C).

Cubic samples were then subjected to destructive uniaxial compressive strength test using an automated press with the capacity of 3000 kN in accordance with the TS EN 12390-3 standard. Adhesive strength of the samples was also tested using the pull-out test method, another destructive method. However, this test was only conducted on the samples with 15x15x15 cm dimensions as thickness is an important variable for this test. INSTRON 8503 Pull-Out Device was used for the pull-out test having the speed set to 2 mm/min.

Ultrasonic pulse velocity test was performed on all the samples as per ASTM C 597-09 standard using an ultrasound measuring device with the sensitivity at 0.1 µs. 2 readings, from four opposing surfaces, were taken and the averages of the results obtained were used.

3.Results

3.1 Assessment of the Ultrasonic Test Results

Samples were investigated using the ultrasonic test method, a nondestructive test method, and implications were derived having assessed the effect of high temperature on the pore structure of concrete (Figure 3). As the ultrasound traveling time will be longer in concrete with higher porosity, natural (stream) and crushed stone aggregates showed similar properties, while the ultrasonic pulse velocity of the concrete produced using limestone and pumice were relatively higher (Figure 3). Among the control aggregates, the lowest ultrasonic pulse velocity was found for concrete with lightweight (pumice) aggregate with 3,4 mm/µs while the highest ultrasonic pulse velocity was found for concrete with crushed stone aggregate with 4,83 mm/µs (Figure 3). A closer look into the ultrasonic pulse velocity of concrete subjected to high temperatures showed that the velocity decreases by 21% at 300 ºC, by 65% at 600 ºC, and by 85% at 900 ºC. The results showed that the thermal incompatibility between aggregate and cement paste under the effect of high temperature increases the porosity, therefore decreases the ultrasonic pulse velocity (Figure 3) Kristensen and Hansen (1994) reported similar findings in their study.

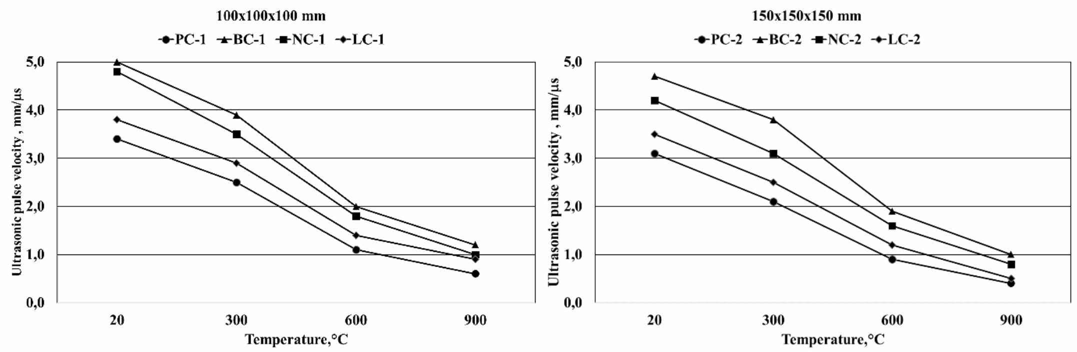

Figure 3. The relationship between ultrasonic pulse velocity (UPV) and temperature for the samples of 100x100x100 mm and 150x150x150 mm in size.

3.2. Assessment of the Compressive Strength Results

Each hardened concrete sample was subjected to compressive strength test. These tests revealed the relationship between high temperature and compressive strength of the concrete. The results showed that series with crushed stone aggregate offers the highest compressive strength while series with lightweight aggregate offers the lowest (Figure 4). It was detected that the loss of strength of the concrete subjected to high temperatures was 5%, 45% and 70%, respectively, for 300 ºC, 600 ºC and 900 ºC (Figure 4). The solid elements of the calcium silicate hydrate (CSH) which makes up the gel texture of the cement paste binds with the help of adsorption water. Adsorption water of the gel and chemically bound water in hydrates start to evaporate at 300 ºC, while the water available in capillary voids may start to evaporate at around 100 ºC. Evaporated water results in retreat. The retreat and the vapor pressure building up in concrete results in cracks in the concrete and therefore material removal. Thus, it leads to decreased compressive strength for the concrete subjected to high temperature. Nevertheless, compressive strength of the concrete produced using three different aggregates (pumice, limestone and stream aggregate) was found to be 10 MPa at 900 ºC. (Figure 4)

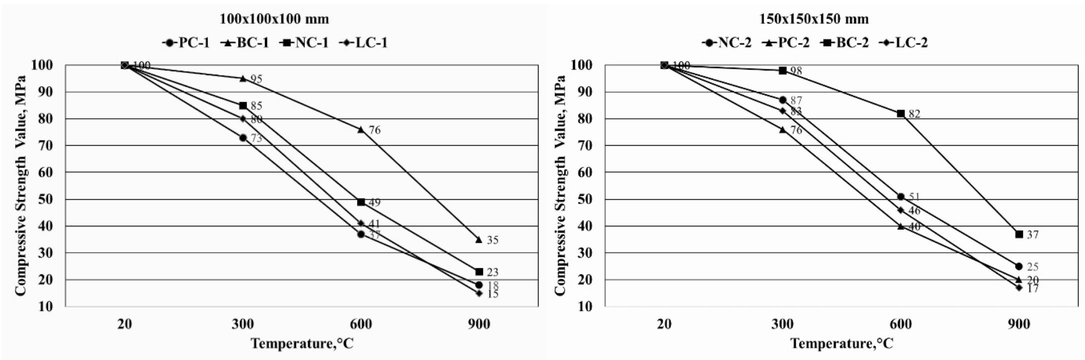

Figure 4. The relationship between compressive strength and temperature for the samples of 100x100x100 mm and 150x150x150 mm in size.

In this study, the relationship between the concrete sample size and high temperature on its compressive strength was also investigated. In addition, the effect of concrete sample size difference on its compressive strength was also investigated under high temperature. The cubic samples of 15 cm^3 in size are found to have a higher compressive strength when compared to the cubic samples of 10 cm^3 in size produced using the same aggregates and methods (Figure 5). Temperature was able to affect the center of small samples when compared to large samples which in return reduced the compressive strength further (Figure 5). Nevertheless, it was found that the concrete produced with different sizes under constant environmental conditions and 900 ºC showed a reduced difference in their compressive strength (Figure 5).

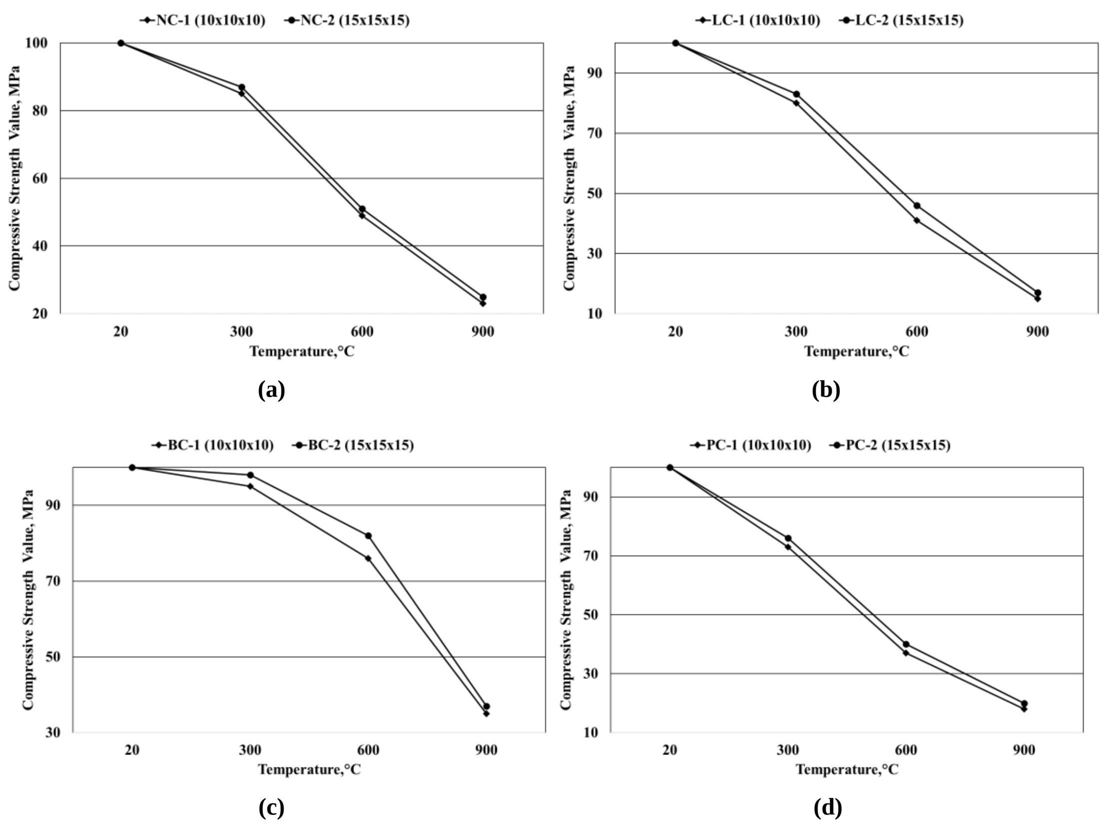

Figure 5. The effect of high temperature on the compressive strength (CS) of concrete produced using the same types of aggregates but in different sizes: (a) naturel aggregate (NC); (b) limestone (LC); (c) basaltic crushed stone aggregate (BC); (d) pumice (PC)

3.3. Assessment of the Pull-Out Test Results

Concrete samples of 150x150x150 mm in size were subjected to pull-out test in order to investigate the effect of high temperature on the adherence strength of concrete. The fact that the cracks in the concrete expand under the effect of temperature and that concrete cannot enclose the equipment sufficiently reduces the adherence strength between concrete and the equipment. The failure of the samples after the pull-out test as shown in Figure 6 offers a better picture of the findings.

Figure 6. Failures in the samples after the Pull-Out Test.

The decrease in adherence strength is evident in Figure 10 which shows the adherence strength with respect to temperature. It was found that the adherence strength of concrete produced with crushed stone was higher for each temperature point when compared to other concrete mixes and that adherence strength of concrete with stream aggregate follows concrete with crushed stone. It was found that adherence strength of concrete with limestone and lightweight aggregate are lower (Figure7).

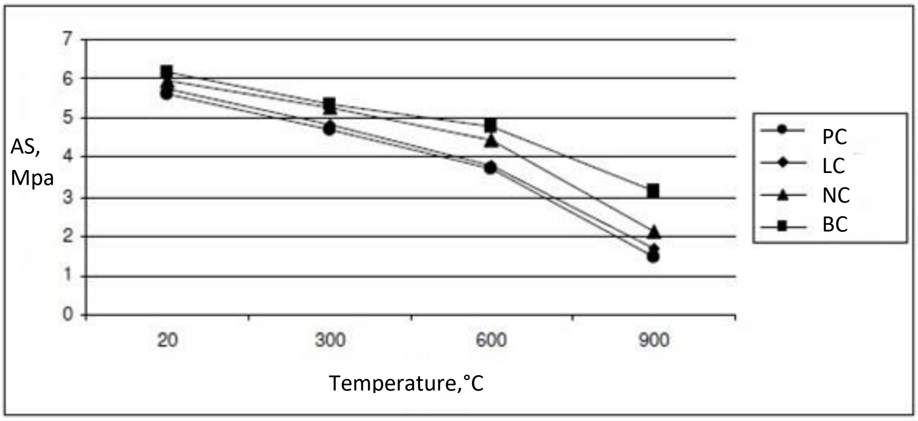

Figure 7. The relationship between adherence strength (AS) and temperature for samples of 150x150x150 mm in size

4. Conclusions

The results of this study, in which the effects of high temperature was investigated for concrete produced using different types of aggregates, as follows:

- In comparison with the control samples, ultrasonic pulse velocity of concrete with crushed stone and stream aggregate were similar, while it was lower for concrete with limestone and lightweight aggregate.
- As the thermal incompatibility between cement paste and aggregate increases the total pore volume of the concrete under the effect of high temperature, ultrasonic pulse velocity of the concretes with aggregate were lower than that of control samples.
- According to the compressive strength results, it was found that concrete produced with lightweight aggregate showed reduced loss in strength due to aggregate structure and it was lower than the remaining three aggregates.

- The size difference of concrete samples was found to affect the compressive strength under the effect of high temperature. As the impact of high temperature to the core of all the concrete samples (of 15 cm^3) was delayed, the effect of high temperature was reduced with the increasing size and they gave higher compressive strength results when compared to the samples of 10 cm^3.
- Compressive strength of the samples of 10 cm^3 and 15 cm^3 was found to be different at a range between 0.90 to 0.93.
- The results of the pull-out test showed that increased temperature results in reduced adherence strength between concrete and the equipment.

According to the results of this study, concrete produced with crushed stone aggregate was found to offer the optimal yield under high temperature. It was found that there is a relationship between increased/decreased durability of concrete with respect to high temperature and the concrete size. We believe this study will pave the way for future studies in this field.

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