

## Ultrasonic Pulse Velocity and Compressive Strength Evaluation of Concrete Containing Fly Ash Exposed to High Temperatures

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### Abstract

Concrete is frequently subjected to various adverse environmental effects throughout its service life such as fire and high temperature. Although the resistance of concrete against fire is superior to many other construction materials up to a certain temperature, its performance starts to decrease at temperatures above 400°C. Serious physical and mechanical damage starts to take place particularly above 400°C and the performance of concrete decreases due to such impacts.

Fly ash is an artificial pozzolanic material that can be used as a mineral additive in making concrete. Fly ash has on the one hand a beneficial effect on the performance of the concrete and allows economy by saving cement on the other hand as it is a waste product of thermal power plants.

In this study, the compressive strength and ultrasonic pulse velocities of concrete containing fly ash subjected to high temperatures was investigated. The measurements were taken at the end of 28 days of standard curing and 28 days of standard curing plus 90 days of air curing in a laboratory condition. Concretes of 300 kg/m<sup>3</sup> were produced and fly ash was replaced with cement at ratios of 20%, 30% and 40% by weight of cement. The ultrasonic and compressive strengths measurements were taken on 100 mm cubes. The temperatures applied to concrete were 200°C, 400°C, 600°C, and 800°C, respectively.

It has been found that fly ash substitution does not have a beneficial effect on concrete subjected to high temperature both in ultrasonic pulse velocity and compressive strength.

**Keywords:** High temperature, fly ash, ultrasonic pulse velocity, compressive strength.

## Yüksek Sıcaklığa Maruz Uçucu Kül İçeren Betonun Ultrases Geçiş Hızı ve Basınç Dayanımının Değerlendirilmesi

### Öz

Beton servis ömrü boyunca yangın ve yüksek sıcaklık ve benzeri çeşitli olumsuz çevresel etkilere maruz kalır. Betonun yangına karşı direnci belirli bir sıcaklığa kadar diğer birçok yapı malzemesinden daha üstündür. 400°C'nin üzerindeki sıcaklıklarda ciddi fiziksel ve mekanik hasarlar oluşmaya başlar ve bu etkiler nedeniyle betonun performansı düşer.

Uçucu kül beton üretiminde mineral katkı olarak kullanılan yapay puzolanik bir malzemedir. Uçucu kül kullanımı betonun performansı üzerinde olumlu bir etki oluştururken termik santrallerin atık bir ürünü olduğu için betonda kullanılması ekonomik ve çevrecidir.

Bu çalışmada, yüksek sıcaklığa maruz kalmış uçucu kül içeren betonun basınç dayanımı ve ultrases geçiş hızı araştırılmıştır. Ölçümler 28 gün standart kür ve 28 gün standart kür ve ardından 90 gün laboratuvar ortamında kür edilmesi sonunda gerçekleştirilmiştir. Betonlar 300 kg/m<sup>3</sup> bağlayıcı dozajında ve uçucu kül çimento ile ağırlıkça %20, %30 ve %40 oranlarında ikame edilerek üretilmiştir. Ultrases ve basınç dayanımı deneyleri 100 mm küp numuneler üzerinde gerçekleştirilmiştir. Uygulanan sıcaklıklar sırasıyla 200°C, 400°C, 600°C ve 800°C'dir.

Uçucu kül ikamesinin yüksek sıcaklığa maruz betonun hem ultrases geçiş hızı hem de basınç dayanımına olumlu bir etki sağlamadığı görülmüştür.

**Anahtar Kelimeler:** Yüksek sıcaklık, uçucu kül, ultrases geçiş hızı, basınç dayanımı.

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## 1. Introduction

Concrete is a building material that performs very well under the influence of fire as it is generally behaves to other external effects. In this sense, concrete can sustain its fire-related performance for a relatively long time [1]. Some physical and chemical changes occur during the fire when the temperature is above a certain level [2]. The reasons for this are the changes in the physical properties of the cement paste and the aggregate [3-6].

The thermal properties of concrete are related to thermal conductivity, thermal expansion, thermal diffusion coefficients and specific heat values. Resistance to high temperatures of concrete is closely related to its main constituent aggregates and its mineral composition [7].

Water in the cement paste can be found as hydrated water in the cement gel, in the gel pores, and as free water in the capillary gaps. Free water in the capillary gaps evaporates when the temperature of concrete exceeds 110°C [8 and 9]. When the temperature reaches 300°C, the thermal expansion in the aggregate causes internal tension of concrete to increase. In case the temperature exceeds 300°C, the separation of the non-evaporating chemically bound water under normal conditions increases the damage level of concrete [3]. In case the temperature reaches 400°C, the calcium hydroxide in the cement paste breaks into calcium oxide and water. This leads to a volume reduction of approximately 33% [6, 10 and 11]. When the temperature reaches 600°C, the hydration product calcium-silicate-hydrate, which is responsible for the strength of the cement, is destroyed. Besides this, the cement paste shrinks and a significant decrease in strength occurs [6, 10-12]. When the temperature reaches 800°C, it's about to breakdown of the concrete completely and further the concrete is going to be disintegrated [5, 13 and 14].

Depending on the increasing temperature, the change in the mechanical properties of concrete is related to many parameters. Some of these parameters are the physical and chemical properties of the materials, and the type and the amounts of additives used [15].

The purpose of this study is to investigate the changes in the compressive strength and the ultrasonic pulse velocity of concretes containing fly ash at high temperatures. Measurements were taken at the end of 28 days of standard curing and 28 days of standard curing plus 90 days of air curing in a laboratory condition.

## 2. Material and Methods

### *Materials*

Calcareous crushed aggregate with a maximum grain size of 16 mm and crushed sand were used in the study. The particle density at SSD state, water absorption and the moisture content of the aggregates are given in Table 1. The gradation of the aggregate mixture along with the reference curves is given in Figure 1.

**Table 1.** Particle density, water absorption, and moisture content of aggregates

Aggregate	Particle density, Mg/m <sup>3</sup>	Water absorption, %	Moisture content, %
Coarse aggregate (Crushed stone)	2.74	1.00	0.15
Crushed sand	2.60	3.00	1.00

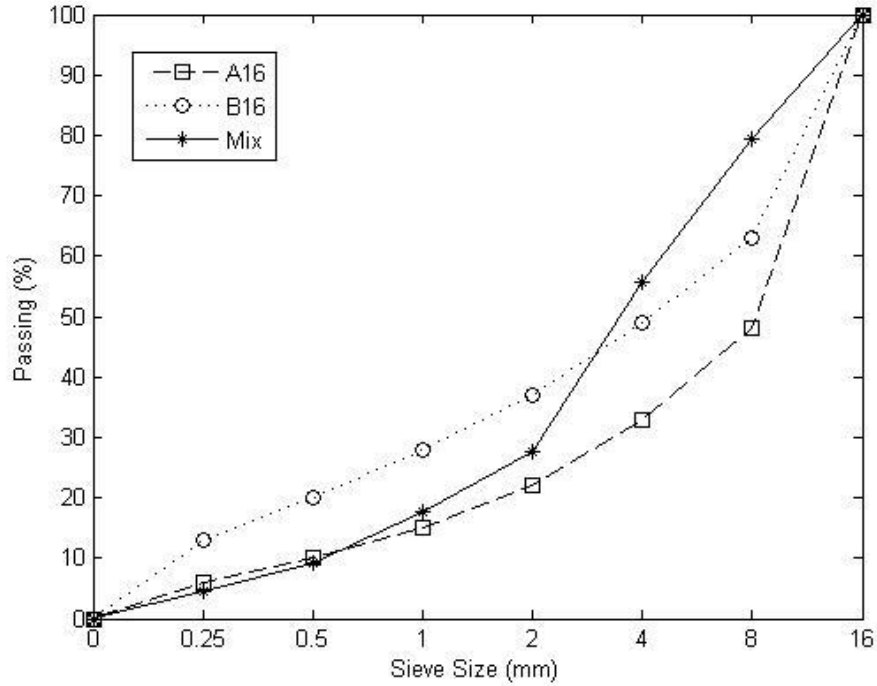


Figure 1. The gradation of the aggregate mix and the reference curves

The cement used in the study was CEM I 42.5 R type, manufactured by Aşkale Trabzon Cement Factory. Some properties of the cement used are given in Table 2.

Table 2. Chemical composition, physical and mechanical properties of cement

Chemical Composition		Physical and Mechanical Properties		
Oxides	Content, %	Retained on 45 µm sieve, %	9.8	
SiO <sub>2</sub>	19.46	Retained on 90 µm sieve, %	1.0	
Al <sub>2</sub> O <sub>3</sub>	5.11	Specific surface (Blaine), m <sup>2</sup> /kg	412.6	
Fe <sub>2</sub> O <sub>3</sub>	3.31	Particle density, Mg/m <sup>3</sup>	3.12	
CaO	60.23	Setting times (Vicat), min.	Initial	140
MgO	2.08		Final	200
SO <sub>3</sub>	3.05	Water demand, %	29.2	
Na <sub>2</sub> O	0.27	Soundness, mm	1.0	
K <sub>2</sub> O	0.69		2-day	28.0
Cl	0.02	Compressive strength, MPa	7-day	40.4
Loss on ignition	3.00		28-day	51.5

The fly ash was obtained from Zonguldak-Çatalağzı power generation plant. The chemical composition of the fly ash is given in Table 3. A superplasticizer type chemical admixture was also used in the production of the mixes.

**Table 3.** Chemical composition of fly ash

Density (g/cm <sup>3</sup> )	2.34
SiO <sub>2</sub> (%)	61.57
Al <sub>2</sub> O <sub>3</sub> (%)	20.25
Fe <sub>2</sub> O <sub>3</sub> (%)	7.30
CaO (%)	1.54

*Mixture proportions*

The mix proportions of the concretes are given in Table 4. The amount of binder and the water to cement ratio were kept constant as 300 kg/m<sup>3</sup> and 0.60 for all mixes, respectively. Thirty 100 mm cube specimens were produced for each batch. All specimens were demolded 24 hours after the production is performed.

**Table 4.** Mix proportions of the concretes produced

Designation of the mixes	Replacement ratio for the fly ash, %	Amount of constituent materials, kg/m <sup>3</sup>			
		Cement	Water	Aggregate	Fly ash
300PC	0	300		1885	0
300FA20	20	240	180	1879	60
300FA30	30	210		1876	90
300FA40	40	180		1874	120

Thirty 100 mm cube specimens were prepared for each batch. All specimens were placed in standard curing condition for 28 days. Then fifteen specimens were subjected to ultrasonic pulse velocity and the compressive strength tests. The rest 15 specimens were placed in a laboratory condition for additional 90 days of air curing and then ultrasonic pulse velocity and the compressive strength tests were performed. Thus, the tests were performed for two different curing conditions. At the end of each curing condition, three specimens from each casting were subjected to ultrasonic pulse velocity and compressive strength tests after the exposure to high temperature at 200°C, 400°C, 600°C, and 800°C. Furthermore, three specimens from each casting and each curing condition were subjected to testing without subsection to high temperatures.

The oven used for the high temperature exposure and the samples exposed to high temperature are shown in Figure 2.



**Figure 2.** The oven used for the high temperature exposure and the specimens

The ultrasonic pulse velocity test setup is shown in Figure 3. In the test, the transit time of ultrasonic sound through the specimen was measured. A gel was used on the faces of the specimen to provide high conductivity. The average duration of the transit time was taken as the average of the measurements of both sides of the specimen. Subsequently, the ultrasonic pulse velocity was calculated by dividing the specimen length by the measured transit time. Measurement of ultrasonic pulse transition times were not possible due to high level of damage occurred at 800°C.



**Figure 3.** Ultrasonic pulse velocity test set up

**Table 5.** Pulse velocity ratings for concrete quality grading [16]

Pulse Velocity (km/s)	Quality Grade of Concrete
> 4.5	Excellent
3.5-4.5	Good
3-3.5	Medium
< 3.0	Poor

Compressive strengths were determined on 100 mm cube specimens as seen in Figure 4. The compressive strength test was performed according to TS EN 12390-3 [17].



**Figure 4.** Execution of compressive strength test on concrete specimen

### 3. Results and Discussion

#### *Ultrasonic pulse velocity*

Figure 5 and Figure 6 show the ultrasonic pulse velocity measurements for concretes containing fly ash at replacement ratios of %0, %20, %30, %40 and concrete exposed to a laboratory condition at 25°C and at high temperatures following 28 days of standard curing.

Figure 5 indicates that the ultrasonic pulse velocity of concretes decreases as the replacement ratio of fly ash increases. This is valid for all exposure temperatures. The decrease is quite significant more obvious for concretes subjected to 400°C and 600°C. Similarly, as can be seen from Figure 6, the ultrasonic pulse velocity of concretes decreases as the temperature increases. Considering both graphs, it can be concluded that incorporation of fly ash in concrete adversely affects the concrete in relation with its ultrasonic pulse velocity.

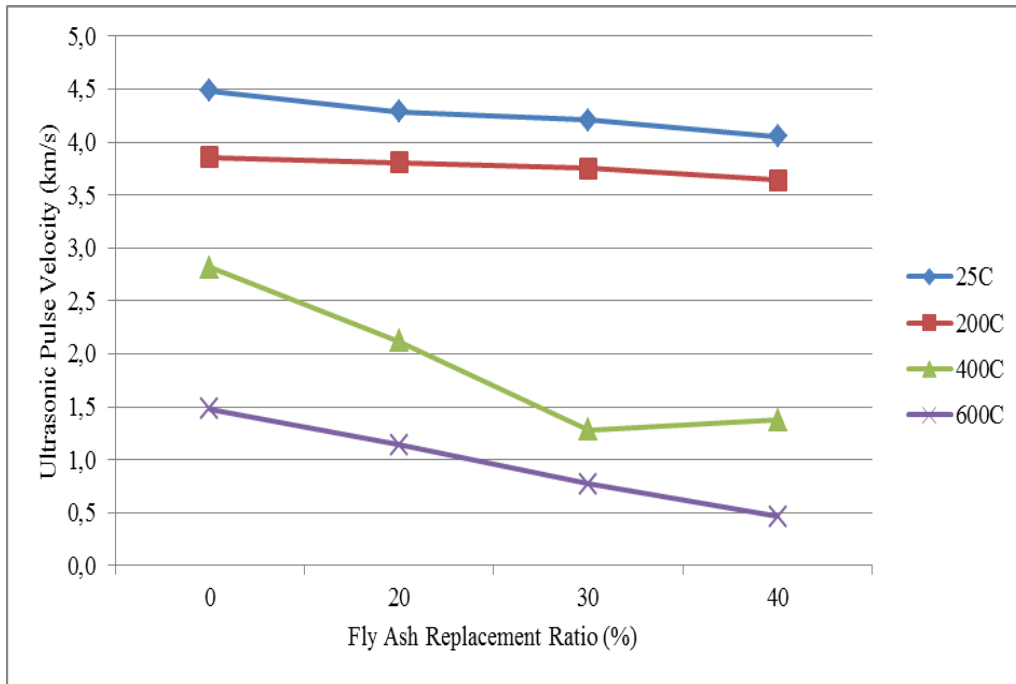


Figure 5. Relation between ultrasonic pulse velocity versus fly ash replacement obtained at the end of 28 days of standard curing

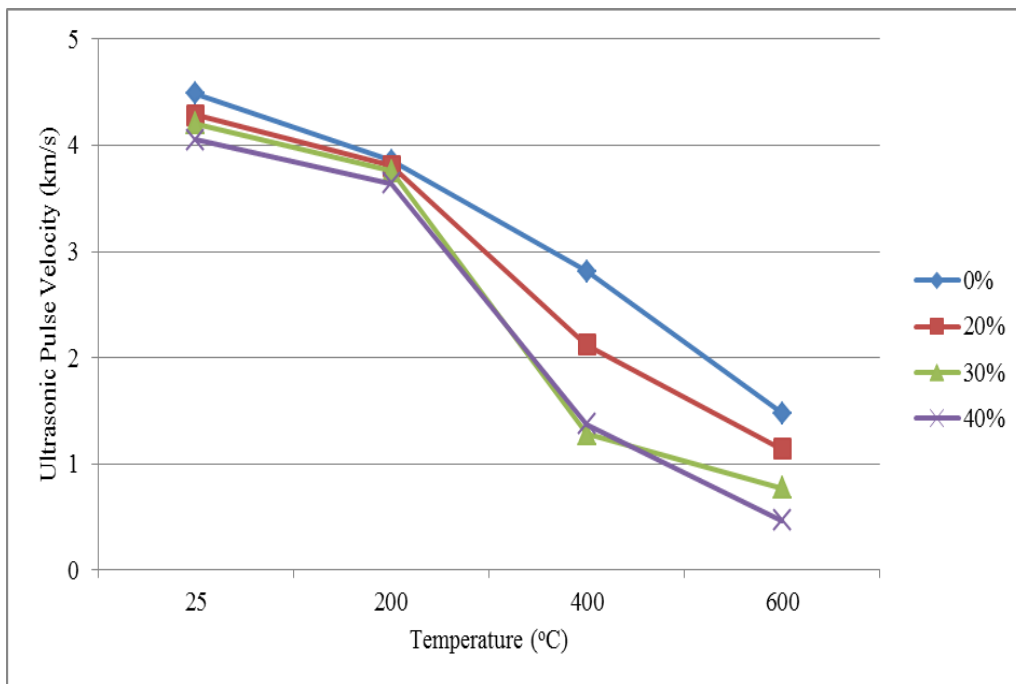


Figure 6. Relation between ultrasonic pulse velocity versus temperature obtained at the end of 28 days of standard curing

Figure 7 and Figure 8 show the ultrasonic pulse velocity of concretes containing fly ash measured following 28 days of standard curing plus 90 days of air curing in a laboratory condition. As can be seen from both figures, the use of fly ash in concrete adversely affects the ultrasonic pulse velocity of concretes in such a curing condition. However, longer curing seems to be beneficial on concretes exposed to 400°C and 600°C concerning to ultrasonic pulse velocity. In another word, prolonging the curing time obviously increases the ultrasonic pulse velocity of concrete.

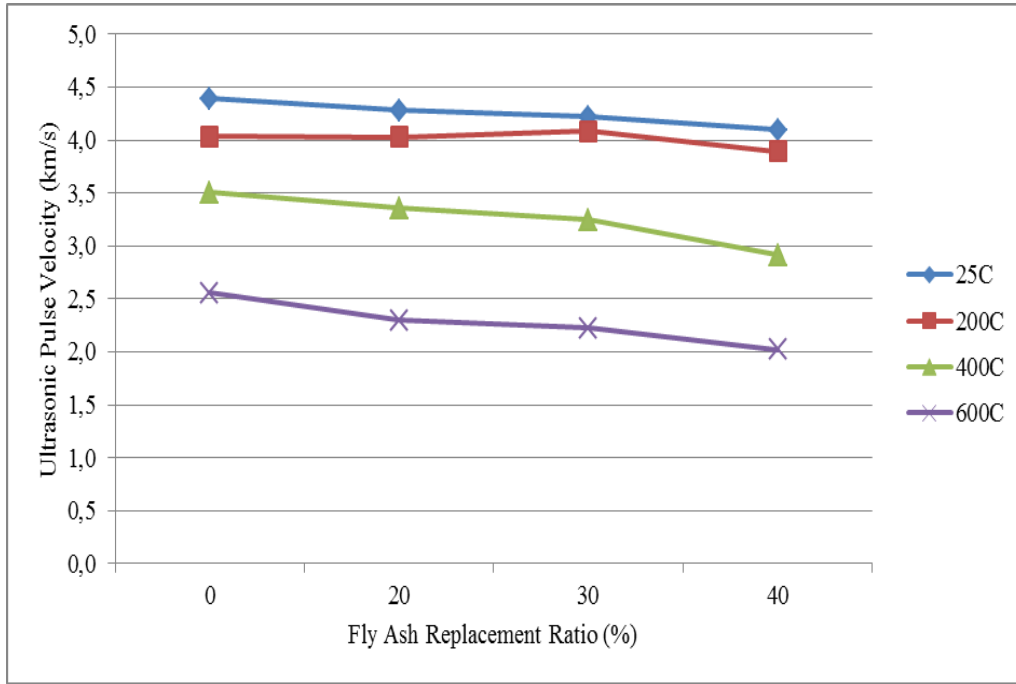


Figure 7. Relation between ultrasonic pulse velocity versus fly ash replacement obtained at the end of 28 days of standard curing plus 90 days of air curing in laboratory condition

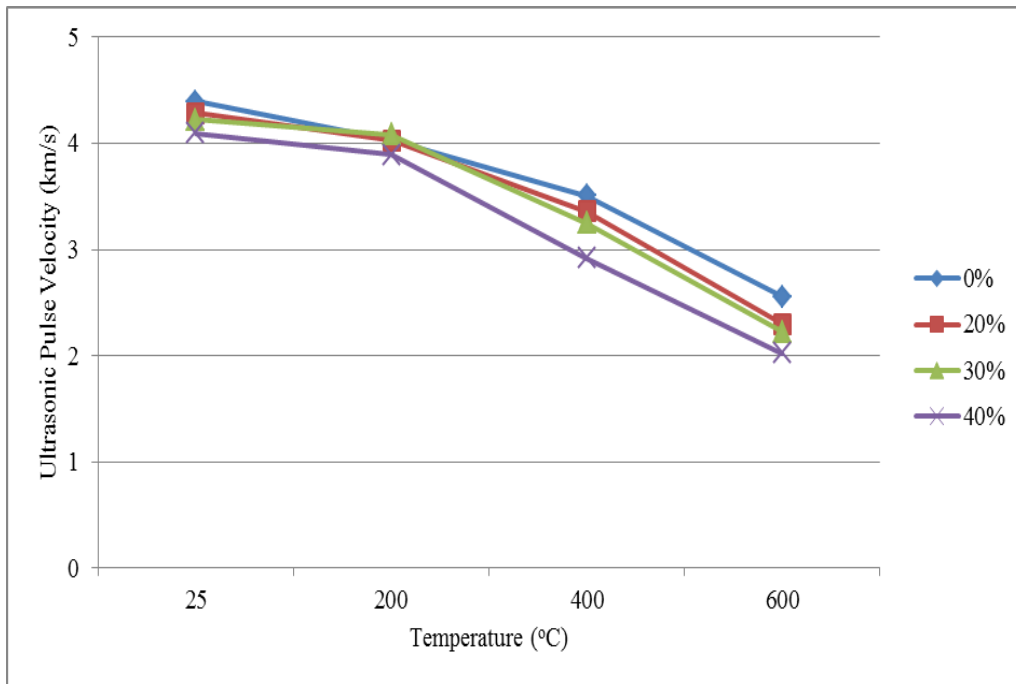


Figure 8. Relation between ultrasonic pulse velocity versus temperature obtained at the end of 28 days of standard curing plus 90 days of air curing in laboratory condition

In a study performed [18], it has been stated out that ultrasonic pulse velocity of concrete decreases as the incorporation of fly ash increases. This result is quite similar to the results obtained in the present study.

#### Compressive Strength

Figure 5 and Figure 6 show the compressive strengths of concretes containing fly ash at replacement ratios of %0, %20, %30, %40 and concrete exposed to a laboratory condition at 25°C and at high temperatures following 28 days of standard curing. When Figure 9 is closely examined, the



compressive strength decreases as the replacement ratio fly ash increases for all exposure temperatures. Figure 10 indicates that the compressive strengths of concretes subjected to 200°C and 400°C are higher than the strength of concrete at 25°C. The reasons for this may be attributed to the beneficial effect of temperatures up to 400°C on hydration process of concrete. On the contrary, temperatures above 400°C have an adverse effect on the compressive strength of concrete as concrete decomposes internally at such temperatures.

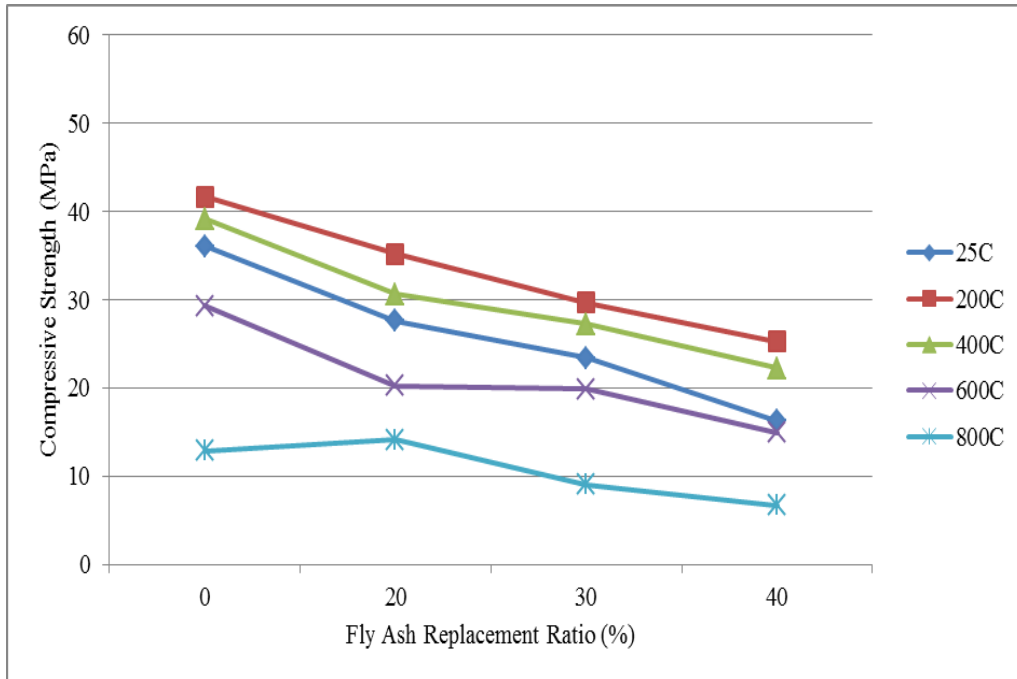


Figure 9. Relation between compressive strength versus fly ash replacement obtained at the end of 28 days of standard curing

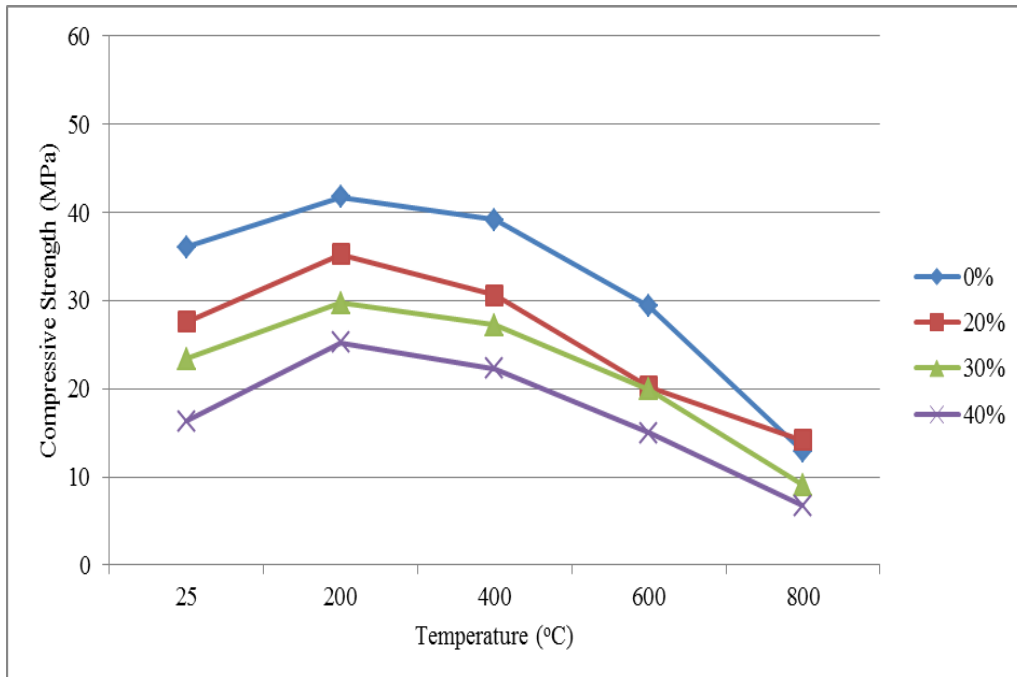


Figure 10. Relation between compressive strength versus temperature obtained at the end of 28 days of standard curing

Figure 11 and Figure 12 show the compressive strengths of concretes containing fly ash measured following 28 days of standard curing plus 90 days of air curing in a laboratory condition. Figure 11 clearly indicates that the compressive strength of concrete decreases as the replacement ratio of fly ash increases. The compressive strengths of concretes subjected to high temperatures is lower compared to the compressive strength of concrete at 25°C for all replacement ratios of fly ash. This behavior is rather different from that of observed in Figure 10. This may be attributed to the beneficial effect of longer curing time on the hydration process of concrete since the hydration process.

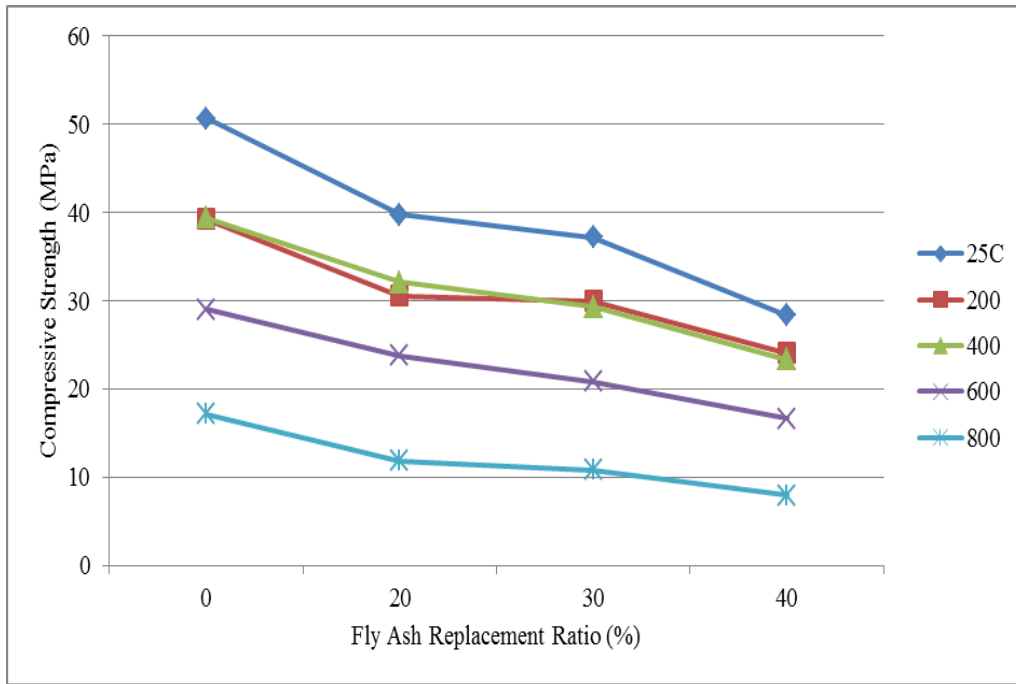


Figure 11. Relation between compressive strength versus fly ash replacement obtained at the end of 28 days of standard curing plus 90 days of air curing in laboratory condition

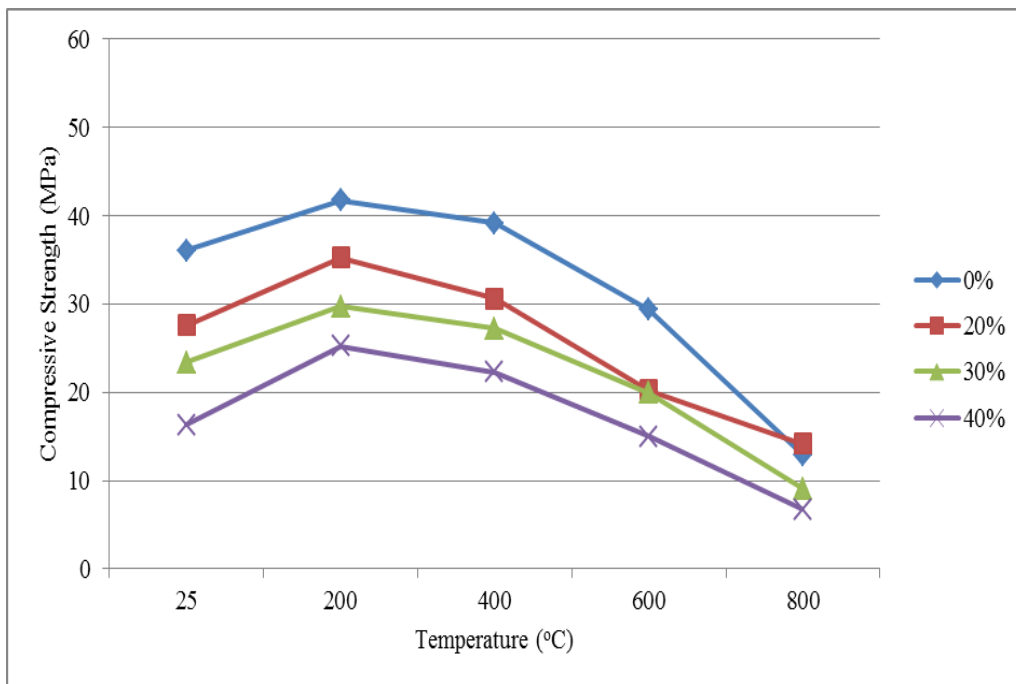


Figure 12. Relation between compressive strength versus temperature obtained at the end of 28 days of standard curing plus 90 days of air curing in laboratory condition

In a study carried out [18], it was stated that the compressive strength of concrete decreases as the fly ash replacement ratio increases that this result is quite parallel to the results obtained from the present study.

#### 4. Conclusions

Based on the experimental study performed on the effects of high temperature on the ultrasonic pulse velocity and compressive strength of concrete containing fly ash, the following main conclusions may be drawn:

- The use of fly ash in concrete has an adverse effect on the ultrasonic pulse velocity and the compressive strength of concrete subjected to high temperatures.

- Exposure temperatures above 600°C is highly destructive, particularly for concretes with a fly ash replacement ratio of %40.

- If the targeted strength is achieved, using fly ash in concrete exposed to temperatures below 400°C can be considered economically beneficial.

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