# Experimental and Statistical Analysis of the Impact Resistance, Compressive Strength and Ultrasonic Pulse Velocity of Normal and High Strength Concrete Exposed to Elevated Temperatures

Marva Angela Blankson[a,*]

Savaş Erdem [b]

[a] School of Civil Engineering, The University of Nottingham, Nottingham-UK

[*, b] Corresponding author, Department of Civil Engineering, University of Istanbul, Avcilar Campus, Istanbul-Turkey

## Abstract

*Based on normal strength concrete and high strength concrete, with compressive strengths of 30 and 50 MPa respectively, damage to concrete under elevated temperatures was studied. After exposures to temperatures up to 500 °C, impact resistance, compressive strength, density and ultrasonic pulse velocity of the mixtures were determined. In addition; a statistical programme was used to establish a relationship between the impact strength and the compressive strength and temperature of the two types of concrete. The results indicate that the compressive strength of the concretes decreased as the temperature of the concrete increased but the percentage decline in the residual compressive strength is much higher in the high strength concrete than in the normal strength concrete. Further, for both high strength and normal strength concrete samples, the percentage loss in the residual strength with rise in temperature was greater in the impact strength than in the compression strength. Finally, it was found from the statistical analysis that there was a very strong inverse relationship (R<-0.9) between the impact strength and temperature of both high strength and normal strength concrete samples.*

**Keywords:** Concrete, High temperature, Impact resistance, Mechanical analysis

## 1. Introduction

The damage caused by fire is one of the most serious risks to structures and building materials in civil engineering. The extensive use of concrete as a structural material has led to the need to fully understand and to be taken into account of the effect of fire on concrete [1].

Although concrete is well-known for its capacity to endure fires [2], its chemical composition and physical structure undergo a series of changes when exposed to elevated temperatures. The primary changes are taken place in the hardened cement pastes starting from the dissociation of portlandite at 400 ºC, and continue until the complete destruction of the calcium-silicate- hydrate (C-S-H) gel at around 900 ºC [3]. As a result of these changes; the compressive strength, modulus of elasticity and volume stability of concrete are significantly decreased [4,5]. In addition, some changes in color [6], and wide cracks and explosive spalling [7] may also occur after high-temperature exposure.

The performance of concrete subjected to high temperatures is governed by many factors including heating rate, peak temperatures, dehydration of C -S-H gel, phase transformation, and thermal incompatibility between aggregates and cement paste [8]. Research studies show that the behavior of high-strength concrete (HSC) subjected to high temperatures is quite different than that of normal strength concrete (NSC) [9-11]. It is reported that HSC has higher rates of strength loss than normal strength concrete [9], and also HSC is more prone to explosive spalling when exposed to elevated temperatures [10]. In addition, the permeability-related durability of HSC subjected to high temperatures is much lower than that of NSC as a result of a greater change in the pore structure (pore-structure coarsening) [11].

A review of concrete literature indicates that in contrast to physico-mechanical and durability properties of concrete exposed to high temperatures, no study has been conducted so far to investigate the dynamic behavior of concrete materials under high temperatures. An attempt was, therefore, made mainly to evaluate the influence of high temperatures on the impact response of two different types of concrete. Moreover, the compressive strength and ultrasonic pulse velocity of the mixtures were also studied, and a statistical programme was used to establish a relationship between the impact strength and the compressive strength and temperature of the two types of concrete.

## 2. Experimental details

CEM I 42.5 R Portland cement was used to produce all the concrete mixes. Local river sand with a specific gravity 2.64 constituted the fine aggregate in all mixes. Crushed granite with 10 mm size was used as coarse aggregate in this study. 150 mm cube specimens were prepared for two grades of concrete named normal strength concrete (NSC) and high strength concrete (HSC). The mix proportions and the 28-days compressive strengths are give in Table 1. All concrete mixtures were batched using a mechanical pan mixer, placed in oiled steel molds in two layers. Each layer was compacted by using a vibrating table before being covered with plastic sheets. The specimens were left in their molds for 1 day before de-molding and cured at 20 ± 2 ºC in water tank until 28-day age. After curing, the specimens were kept at 105 ºC and atmospheric pressure for 24 h for drying.



**Table 1: The mix proportions of concrete samples**

| Mix ID | Cement (kg/m$^3$) | Water (kg/m$^3$) |
|---|---|---|
| NSC | 310 | 205 |
| HSC | 440 | 210 |

The specimens were then heated in an electric furnace (Fig.1) to temperatures of 20 ºC, 300 ºC and 500 ºC. The peak temperature was maintained for 1 h. After that, the specimens had been allowed to cool naturally to room temperature. Finally, the residual compressive strength, impact resistance, ultrasonic pulse velocity and density were determined. The impact tests were carried out by drop- weight method using aggregate impact test (Fig.2). The test method shown is previously used Marar et al. [12]. The impact resistance of the concrete specimens was determined in terms of the number of blows required to either produce the first visible crack or cause complete failure of the specimens.

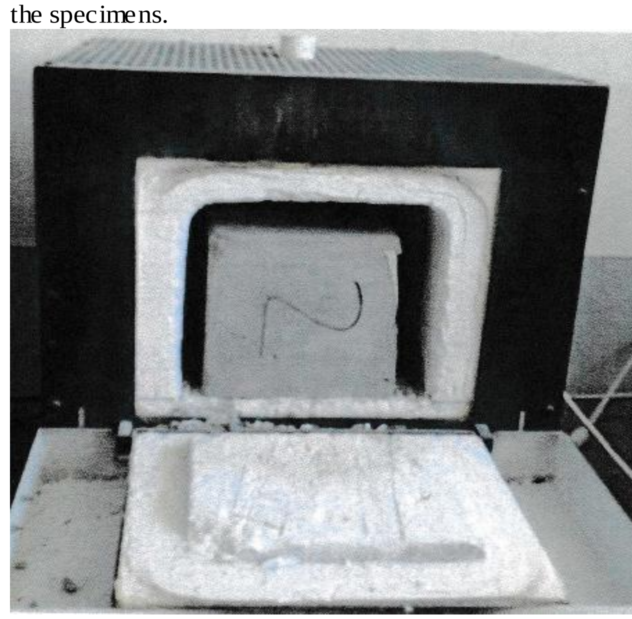

**Fig.1: The specimen in the electric furnace**

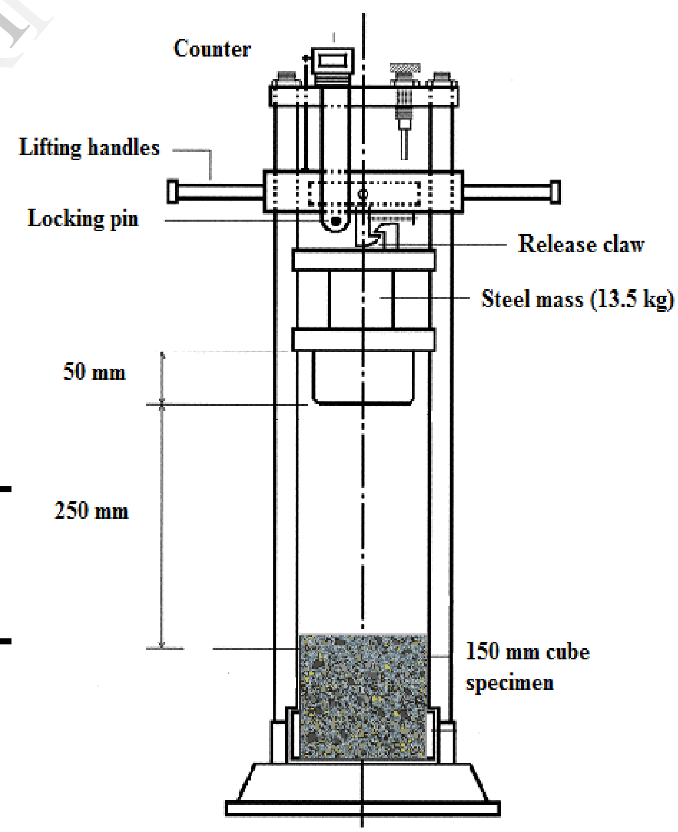


**Fig.2: Impact test machine**

## 3. Results and discussion

### 3.1 Compressive strength and density

From the strength test results in Fig. 3, it is shown that the trend in the relationship of compressive strength versus temperature is the same for both high and normal strength concrete samples. That is, the compressive strength of the concrete decreased as the temperature of the concrete increased.

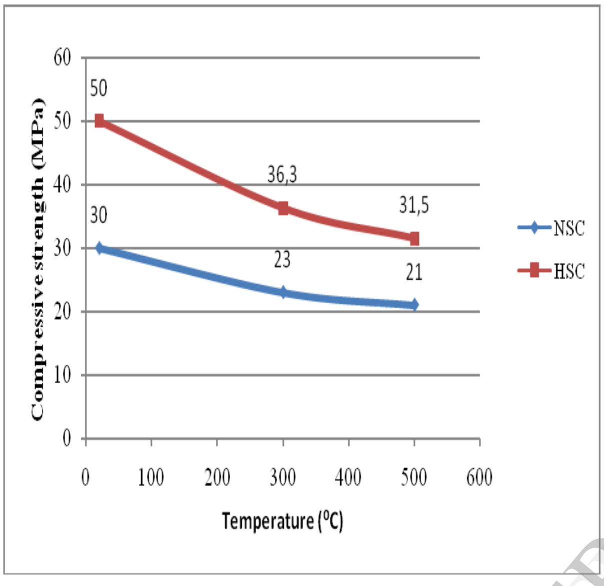


**Fig.3: The relationship of compressive strength versus temperature**

The graphical display of the compressive strength also shows that the percentage decline in the residual compressive strength is higher in the high strength concrete than in the normal strength concrete (Fig.4). The decline in strength as the temperature of the concrete increased is confirmed by other researchers [11] and, with respect to the normal strength concrete, the rate of decline of strength with temperature was found to be both higher and lower in the high strength concrete [11-12].

The reduction in strength is partly ascribed to micro-cracks that are the result of thermal incompatibility between the aggregates and the mortar and to shrinkage. However, the higher rate of strength loss in the high strength concrete sample is attributed to the relatively low pore connectivity and pore volume in the dense microstructure of high strength concrete. When the concrete is subjected to high temperature, these features make it more difficult for vapour to be released [13] in the high strength than in the normal concrete. The vapour pressure that is built up primarily between the dry and moist layers in the concrete also contributes to tensile stresses [5,13] that no doubt contributes to the reduction of the strength and causes a higher rate of decline in strength when the temperature is increased.

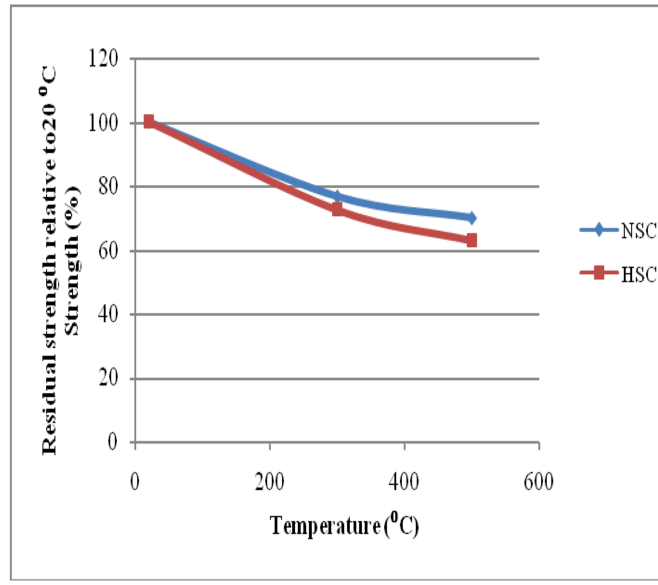


**Fig.4: The residual compressive strength versus temperature**

The reduction in the density of the two types of concrete (Fig. 5) as the temperature is elevated is the result of the dehydration of the various phases of the cementitious material. Research done by Kalifa et al. [14] found that the mass loss in moisture in heated concrete was greater in normal strength concrete than high strength concrete. The percentage mass of water loss was consistently higher in normal strength than in the high strength sample and the reason provided by the researchers was that the higher water content and the higher level of porosity in the former facilitated a greater degree of permeability. The reduction in the mass of concrete is accompanied by a reduction in the mass per unit volume of the material. In the present research, it is shown that although the overall percentage reduction in density was higher in the normal strength, the percentage reduction is higher in high strength concrete at the lower temperature range (20°C and 300°C) and greater in the normal strength concrete at the higher temperature (300 - 500°C). This phenomenon suggests that after the moisture in the outer layer of the high strength concrete is removed, the reduced permeability of this concrete makes it more difficult for moisture in the inner section to be released.

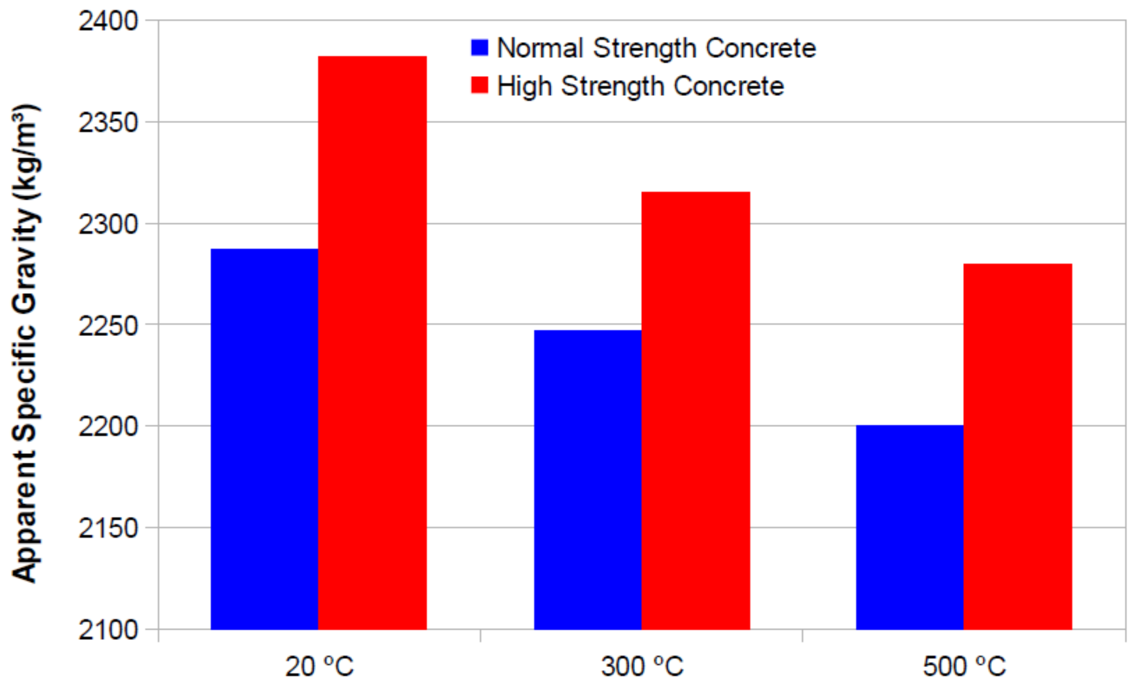


**Fig.5: The relationship of density versus temperature**

### 3.2 Impact resistance

From Table 2 it is seen that the impact resistance of the high strength and normal strength concrete samples also decreased substantially as the temperature moved from 20 - 500°C. More importantly, the rate of loss in impact strength with temperature was larger in the high strength concrete than in the normal strength concrete. Further, for both high strength and normal strength concrete samples, the percentage loss in the residual strength with rise in temperature was greater in the impact strength than in the compression strength (Fig. 6).



**Table 2: Impact test results**

| | Impact resistance (number of blows caused to failure) | | |
|---|---|---|---|
| **Mix ID** | **20 °C** | **300 °C** | **500 °C** |
| NSC | 16 | 11 | 4 |
| HSC | 24 | 18 | 6 |

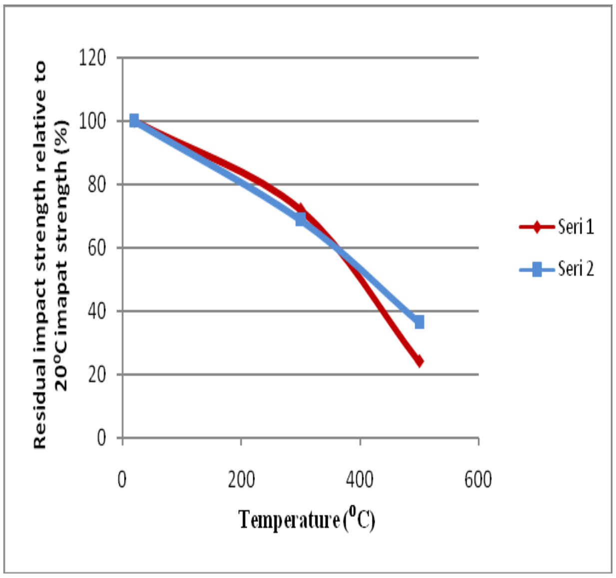


**Fig.6: The residual impact strength versus temperature**

There are two phenomenon that will provide an understanding of the findings. Firstly, it should be said that when static load (as the compression load) is applied to concrete, aggregates, as a result of the usually high strength, deflect micro-cracks that forms in the mortar, and hence the cracking is more likely to extend through the interfacial zone between the aggregate and the mortar [15]. However, when concrete is subjected to impact loading, the sudden concentration in stress does not only produce micro-cracks in the mortar but these cracks may propagate into the aggregates [15]. Secondly, as temperature is increased in concrete, cracks are also developed in the mortar and aggregate; appreciable cracking of mortar occurs in the region of about 120°C [16] and the cracking of the aggregate can be as low as 150°C [17] depending on the type of aggregate and the rate of heating. It can therefore be explained that as the temperature moved from 20 - 500°C, the microstructure of the concrete became more flawed and, the cracks from impact loading could easily be extended into the damaged mortar and into the deteriorated aggregate.

The ease with which the heated aggregate accommodated the extension of cracks shows that the effect of heat had a greater influence on the failure mechanism in the impact loading than that associated with compression loading. Therefore, it is shown that with both high strength and normal strength concrete, the impact resistance is more sensitive to heat than the compressive strength. As the pore pressure would have been greater in the high strength concrete, damage in the high strength concrete would have advanced at a higher rate at elevated temperature than that of the normal strength concrete. This contributed to the higher loss in residual impact strength that was seen in the high strength concrete.



### 3.3 Ultrasonic pulse examination

As moisture is removed in the heating process, dehydration occurs in the C-S-H at 100 – 130 °C and dehydroxylation of the $Ca(OH)_2$ at about 420 – 450 °C [18]. The high temperature also initiates thermal- induced stress that breaks down the mortar and the aggregates. These events contribute to the creation of voids and cracks in the mortar and aggregates.

The discontinuities brought about by these events are detected in the PUNDIT test (Fig. 7). The reduction in the velocity of the transmission of the pulse in the high strength and normal strength concrete samples over elevated temperatures indicates an increase in the heterogeneity of the concrete samples with the rise in temperature. Although the structure of the micro -environment produced a lower level of heterogeneity in the high strength concrete, it is seen that its rate of increase in heterogeneity is higher than that of the normal strength. This condition is also ascribed to the greater effect of vapour pressure in the mortar and aggregates of the high strength concrete under the subjection of high temperature.

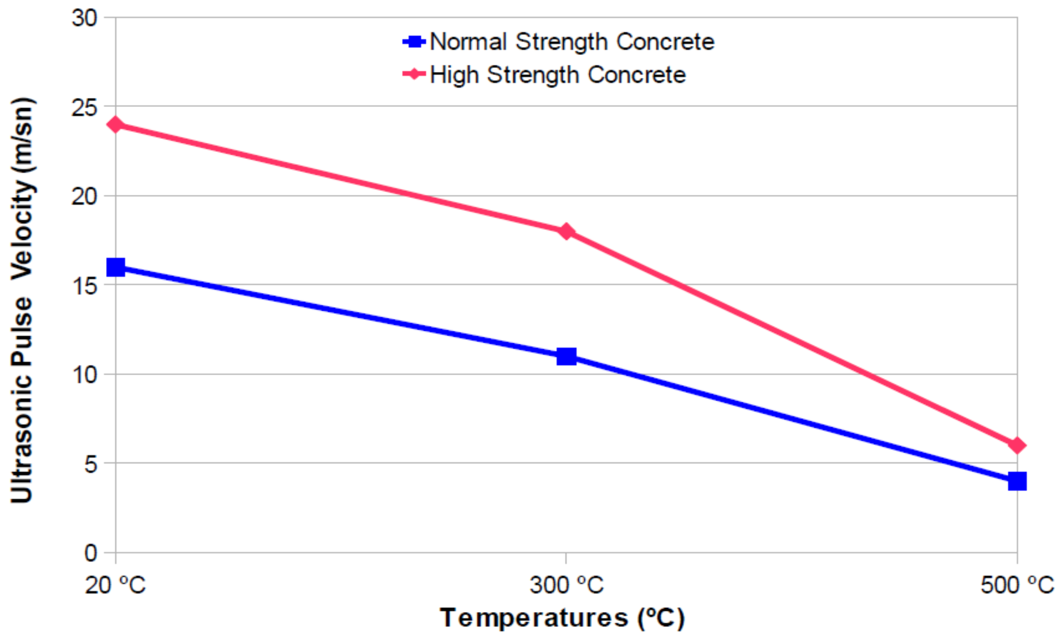


**Fig.7: Ultrasonic pulse velocity versus temperature**

### 3.4 Statistical analysis

From the study it is shown that the compressive strength as well as the temperature affects the impact resistance of the concrete. The coefficient of correlation shows a very strong linear relationship (R>0.9) between the impact resistance and the compressive strength for both the high strength and normal strength types of concrete.

Marar [12], and Nili and Afroughsabet [19] are some of the researchers that report that the compressive strength of concrete is directly proportional to the impact strength. The coefficient of correlation also shows that there is a very strong inverse relationship (R<-0.9) between the impact strength and temperature of both high strength and normal strength concrete samples. A statistical programme was used to carry out a multivariate regression of these parameters in order to establish a relationship between the impact strength ($y$) and the compressive strength ($x_1$) and temperature ($x_2$) of the two types of concrete. The derived relationship is shown in Fig.8 and the significance of each independent variables lies between $1x10^{-4}$ and $6x10^{-5}$. A plot of the residuals versus the predicated in Fig. 8 gives a visual display of the fitting of the equation. The regression values are summarized in Table 3. The values of the coefficients in the derived relationship are also shown in Table 4.

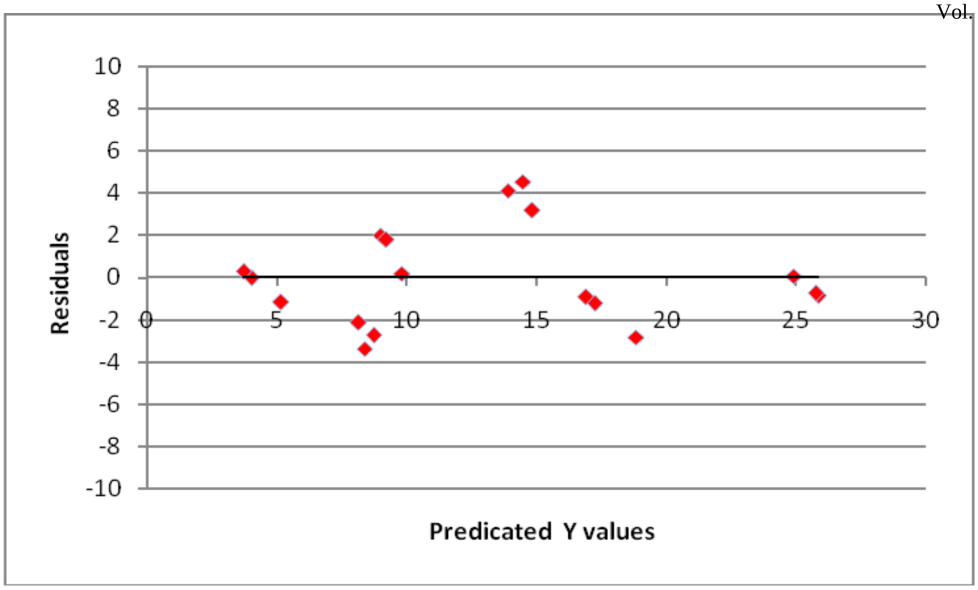


**Fig.8: A visual display of the fitting of the equation**

**Table 3: Summary of the regression statistics**

| Regression statistics | |
|---|---|
| Multiple R | 0,95 |
| R Square | 0,91 |
| Adjusted R Square | 0,89 |
| Standard Error | 2,47 |
| Observations | 18 |



**Table 4: The values of the coefficients**

| | Coefficients | Standard Error | T Stat | P-value | Lower 95% | Upper 95% |
|---|---|---|---|---|---|---|
| Intercept | 6,3218253496 | 3,1845745602 | 1,9851397 | 0,0657268708 | -0,4659346181 | 13,10958532 |
| x2 | -0,0204970732 | 0,0036854194 | -5,5616660 | 5,4404300005 | -0,0283523588 | -0,01264179 |
| x1 | 0,3920443011 | 0,0756341682 | 5,1834285 | 0,0001112261 | 0,2308338885 | 0,5532354714 |

## 4. Concluding remarks

In the light of the findings obtained from this experimental study, the following conclusions can be drawn:

- The impact resistance of the high strength and normal strength concrete samples decreased substantially as the temperature moved from 20 - 500°C.
- The effect of heat had a greater influence on the failure mechanism in the impact loading than that associated with compression loading.
- This can be explained that as the temperature moved from 20 - 500°C, the microstructure of the concrete became more flawed (due to the sudden concentration in stress under impact) and, the cracks from impact loading could easily be extended into the damaged mortar and into the deteriorated aggregate.
- The reduction in the velocity of the transmission of the pulse in the high strength under elevated temperatures was much higher than that of the normal strength concrete samples. This possibly indicates the rate of increase in heterogeneity in the high strength concrete was higher than that of the normal strength.
- The coefficient of correlation indicates a very strong linear relationship (R>0.9) between the impact resistance and the compressive strength for both the high strength and normal strength types of concrete.
- The compressive strength as well as the temperature substantially affects the impact resistance of the concrete.



## References

[1] Y.N. Chan, G.F. Peng and J.K.W. Chan, "Comparison between high strength concrete and normal strength concrete subjected to high temperature," *Materials and Structures, vol. 29, no. 10,* pp. 616-619, 1996.
[2] I. Netinger, I. Kesegic and I. Guljas, " The effect of high temperatures on the mechanical properties of concrete made with different types of aggregates," *F ire Safety Journal, vol. 46, no. 7,* pp. 425-430, 2011.
[3] C.S. Poon, S. Azhar, M. Anson and Y. L. Wong,"Strength and durability recovery of fire-damaged concrete after post-fire-curing," *Cement and Concrete Research, vol.31, no. 9,* pp. 1307-1318, 2001.
[4] O. Arıoz, "Effects of elevated temperatures on properties of concrete," *Fire Safety Journal, vol. 42, no. 8,* pp. 516-522, 2007.
[5] Y.N. Chan, X. Luo and W. Sun, "Compressive strength and pore structure of high performance concrete after exposure to high temperature up to 800 °C," *Cement and Concrete Research, vol. 30, no.2,* pp. 247-251, 2000.
[6] N. Yuzer, F. Akoz and L.D. Ozturk, "Compressive strength-color change relation in mortars at high temperature," *Cement and Concrete Research, vol. 34, no. 10,* pp. 1803-1807, 2004.
[7] R.H. Haddad and L G S hannis, "Post- fire behavior of bond between high strength pozzolanic concrete and reinforcing steel," *Construction and Building Materials, vol. 18, no.6,* pp. 425-435, 2004.
[8] A.F. Bingol, A. Tortum and R. Gul, "Neural network analysis of compressive strength of lightweight concrete after high temperatures," *Materials & Design, vol. 52, no.10,* pp. 258 -264, 2013.
[9] X. Luo, W. Sun and S.Y.N. Chan, "Effect of heating and cooling regimes on residual strength and microstructure of normal strength and high performance concrete," *Cement and Concrete Research, vol. 30, no.3,* pp. 379-383, 2000.
[10] G Sanjayan and L.J. Stocks, "Spalling of high-strength silica fume concrete in fire," *ACI Materials Journal, vol. 90, no. 2,* pp. 170-173, 1993.
[11] Y.N. Chan, GF. Peng and M. Anson, "Residual strength and pore structure of high-strength concrete and normal strength concrete after exposure to high temperatures," *Cement and Concrete Composites, vol. 21, no. 1,* pp. 23-27, 1999.
[12] M. Husem, "The effects of high temperature on compressive and flexural strengths of ordinary and high-performance concrete," *F ire Safety Journal, vol.41, no.2,* pp. 155-163, 2006.
[13] M. Ozawa, S. Uchida, T. Kamada and H. Morimoto, " Study of mechanisms of explosive spalling in high-strength concrete at high temperatures using acoustic emission," *Construction and Building Materials, vol. 37, no.12,* pp. 621-628, 2012.
[14] P. Kalifa, F.D. Menneteau and D. Quenard, "Spalling and pore pressure in HPC at high temperatures," *Cement and Concrete Research, vol. 30, no. 12,* pp. 1915-1927, 2000.
[15] M.H. Zhang, V.P.M. S him, G Lu and C.W. Chen, "Resistance of high-strength concrete to projectile impact" *International Journal of Impact Engineering, vol. 31, no. 7,* pp. 825-841, 2005.
[16] A. Menou, G Mounajed, H. Boussa, A. Pineaud and H. Carre, "Residual fracture energy of cement paste, mortar and concrete subject to high temperatures," *Theoretical and Applied Fracture Mechanics, vol. 45, no. 1,* pp. 64-71, 2006.
[17] Z. Xing, A.L. Beaucour, R. Hebert, A. Noumowe and B. Ledesert, "Influence of the nature of aggregates on the behavior of concrete subjected to elevated temperature," *Cement and Concrete Research, vol. 41, no. 4,* pp. 392-402.
[18] A. Louikili, A. Khelidj and P. Richard, "Hydration kinetics, change of relative humidity, and autogenous shrinkage of ultra-high-strength concrete," *Cement and Concrete Research, vol.29, no. 4,* pp. 577-584.
[19] M. N ili and V. Afroughsabet, "Combined effect of silica fume and steel fibers on the impact resistance and mechanical properties of concrete," *International Journal of Impact Engineering, vol. 37, no.8,* pp. 879- 886, 2010.