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Destructive and Non Destructive Strength Evaluation of Concrete Exposed to Fire

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Abstract

In this investigation concrete of different compressive strength is exposed to fire for various duration similar to natural fire occurring in buildings. A total of 72 Concrete cubes have been cast from three different concrete mixes then exposed to fire up to 1000^{0}C for three different durations (15,30 and 60 minutes) then tested using non-destructive methods like hammer rebound test and Ultra-Sonic Pulse velocity test. Then the cubes were tested to destruction to measure their compressive strength. The results have shown that the unit weight, compressive strength and actual residual strength decreases with the increase of firing exposure duration similar to concrete exposed to steadily rising temperature. The correlation between the cube compressive strength and RN of the hammer test is very close, however the correlation coefficient of the cube strength with the UPV results is less. Using the combined method of the NDT, the relation between the cube strength and the NDT improves. Equations of relation between compressive strength and NDT tests are proposed for use in practice.

Introduction

Concrete strength is measured through destructive tests of concrete cubes cast on site. For the evaluation of existing structures or when the quality of the concrete is in doubt, non destructive tests are performed, which includes among others, the rebound hammer test and ultra sonic pulse velocity tests. Both methods give indication of in-situe concrete quality. Structures are sometimes accidently exposed to fire for various durations. Then, it is almost important to evaluate the residual strength of the structure and its members. Load tests or testing core samples taken from different locations of the member would give best required evaluation results, however both methods would be considered time and cost consuming. A faster and economical process is non destructive tests which can be made at anytime and anywhere on the structure.

NDT had been used by many researchers to evaluate concrete compressive strength, it has been found that using NDT methods on concrete cubes or existing concrete structures show good correlation between actual compressive strength, and predicting from Rebound Hammer No (RN) and Ultrasonic Pulse Velocity (UPV). With these methods the strength within ± 20% accuracy can be achieved, and based on these tests correlation equations have been derived for separate NDT tests or for combined RN with UPV test methods. (Liu, Szilagyi etal, Hamidian etal, Youkhanna, Breyasse, Pocinotti, and Abdulla)[1-7].

NDT had also been used for evaluation of concrete residual strength after exposure to steady rising high temperatures. DiMaio etal [8] used NDT for estimation of damaged concrete due to high temperature exposure. The range of the later was between 150 ^{o}C to 700 ^{o}C, and the strength levels of concrete were between 20 and 60 MPa. The results indicated that contrary to strength, the UPV was the most reliable method to estimate static modulus of elasticity of damaged concrete due to heating. In study of degradation of concrete exposed to high temperatures which is done by Brozovsky etal [9], it was concluded that UPV can be used for that purpose. Kirchoff et al [10] have tested concrete cylinders of different water cement ratios exposed to temperatures ranging from 200 ^{o}C to 600 ^{o}C. After cooling down in air, for each cylinder the UPV and compressive strength were measured. They concluded that the application of UPV is trustworthy on fire damaged concretes.

Umran [11] has studied the effect of fire flame exposure on concrete. Three flame temperature levels were chosen (400, 500 and 700 ^{o}C) with four different exposure times (0.5 to 2 hours). They found that UPV method was more sensitive to fire flame than compressive strength. The residual strength of the cubes, at 700 ^{o}C heating was found that in the range of (43-62%) of the original strength. The same results were observed in Kadhim's [12] tests which have been done on both normal and fibre reinforced concrete cases. Yaqub [13] published a paper presenting results of a fire case attacked a concrete structure in Pakistan. Core samples were taken and NDT technique was used. Results have shown different correlation between destructive and nondestructive tests depending on the type of structural member and type of the NDT, whether RN or UPV. Li and Franssen [14] have carried out an investigation on degradation of compressive strength of concrete due to high temperature, and huge database on previous tests has been presented in the same paper. They have proposed a model for simulating fire response and evaluation of residual strength of concrete structures after fire.

Researches on the effect of heating (steady increasing heat) on concrete properties are many, however studies are very limited in case of firing (sudden exposure to high flame heat) as in natural big fire accident. The aim of this investigation was to find a correlation between concrete compressive strength, and non destructive tests RN from one side and UPV on the other side for different concrete strength before and after its exposure to fire for different exposure duration. Studying the effects of cooling down method by air or quenched in water for various firing exposure duration, were also included in this paper.

Research Significance

Concrete of different compressive strength are subjected to sudden firing process and for various duration similar to natural fire occurring in buildings when cooled down in air or using water fighting. After fire accident, the concrete strength is evaluated by NDT methods and core tests. A correlation equation to be found between compressive strength and the NDTs is of great value for practical use.

Experimental work:

The experimental program consisted of casting 72 concrete cubes (150x150x150 mm) with three different compressive strength levels, for each particular test three identical cubes were cast and tested. The testing was carried out as follows: after casting the cubes and curing in water for 28 days the next day the samples were exposed to fire in a specially made furnace room for the duration as planned, after which the cubes were cooled in air or quenched in water. Next day the cubes were weighted then tested with UPV device and RN measured with the Schmidt hammer while under the compression machine according to standard methods [15, 16], finally tested to destruction under the compression machine. The testing program and cube designations are shown in Table 1, where the first letter denotes the mix type followed by the duration time then the type of cooling.

Table 1. Testing program

mix	cooling type	exposure duration (minutes)			
		0	15	30	60
B	in air	B0	B15A	B30A	B60A
	in water		B15W	B30W	B60W
C	in air	C0	C15A	C30A	C60A
	in water		C15W	C30W	C60W
D	in air	D0	D15A	D30A	D60A
	in water		D15W	D30W	D60W

Materials:

Ordinary Portland cement Type 1, clean river sand and gravel max size 12 mm were used for the concrete mixes. Grading of aggregates were confirming to ASTM C136 [17] specification.

Mix Proportions

All mixes were done by weight, a super-plasticizer was added to increase workability and for each type all the cubes were cast, vibrated on a table and cured in water all together until testing after 28-30 days. Details of the mix proportions are shown in Table 2. The average compressive strength of 3 cubes of each of the three mixes B0, C0 and D0 without firing were 34.5, 49.1 and 54.3 MPa respectively.

Table 2. Concrete mix proportions – by weight ratio

Mix	w/c ratio	cement	Sand	gravel	SP % of cement	f_{cu} MPa
B	0.45	1	1.974	2.895	0.3	34.5
C	0.357	1	1.552	2.217	0.6	49.1
D	0.3	1	1.17	1.62	1.2	54.3

Firing process:

A special chamber as shown in Figure 1 was constructed from fire bricks for the firing process. The size of the chamber was 1200x1200x480 mm enough to accommodate two firing source and six cubes put above the two fire sources so 3 cubes for each one. The fire place covered with steel plate 6 mm thick strengthened at the edges with steel angles and filled with sand. Two thermo-couples were inserted in the fire place to measure the firing temperature. One was put on top of one of the cubes and the other close to the fire flame. The temperatures were measured through a digital instrument as shown in Figure 2. The temperature was also measured externally from outside using a gun like electronic laser temperature measurement device shown in Figure 2 pointed to the side surface of the cubes through holes left in the chamber wall for this purpose.

Figure 1: Firing furnace chamber

Figure2 Measuring devices

The firing process began with putting the cubes on the steel grid above the fire source and covering the chamber. Liquid Propane gas in steel containers was used as a fire source. The Fire source were lit and testing started while measuring the temperatures every 5-10 minutes according to the duration. The temperature of the first thermocouple which measures the flame temperature would rise quickly and reached 600-700^{0}C within minutes, however the temperature of the second one which measures the top surface of the concrete cube have a gradual rising trend as shown in Figure 3.

The actual firing temperature relationship with time of Figure 3 is similar to the standard temperature – time curve of ISO 834 from Eurocode 1 [18] as shown in Figure 4. The concrete surface temperature in Figure3 is the average of the measurements from the thermocouple and the laser devise. When the required duration was reached, the fire source was turned off and the steel plate cover was removed and the cubes were taken out. Three of the cubes were left on the ground to cool in the air. The other three cubes were immersed in a bucket (quenched) and left to be cooled until they can be removed by hand. Once cooled to room temperature the cubes were tested in the same day or in the next day for UPV then RN and finally to destruction.

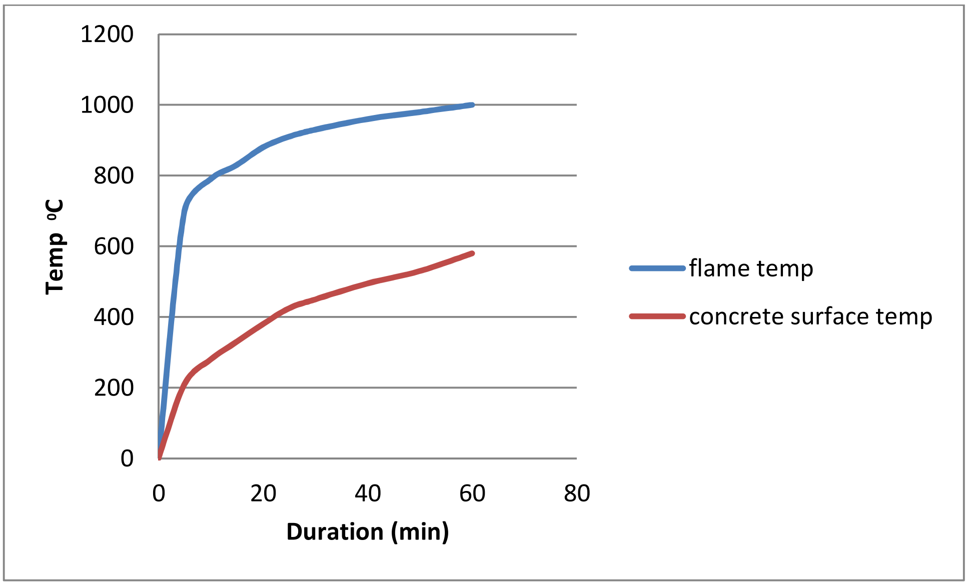

Figure 3 Temperature rise vs. duration (fire source and concrete)

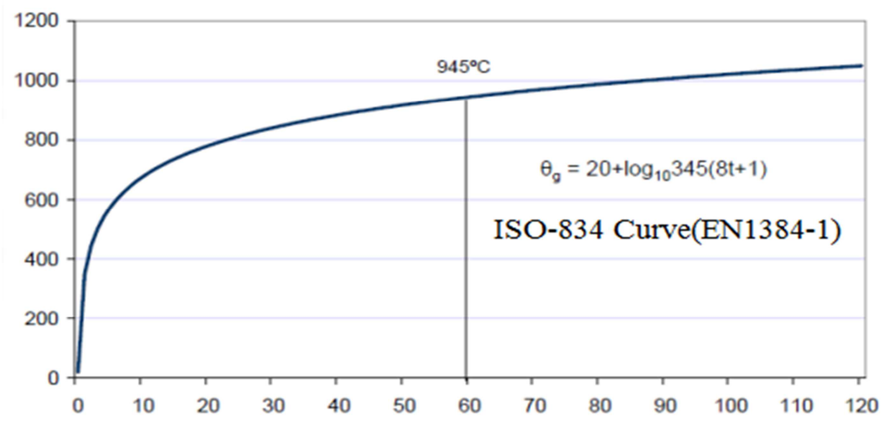

Figure 4 Standard Temperature - Time curve Eurocode 1[18]

The control cubes are those denoted B0, C0 and D0 with no firing, they were all tested in the same day with their exposed to fire companion. The firing temperature reached around 1000^0C for 60 minutes duration, for the purpose of comparison it was decided to test 3 cubes of each mix under steady rising temperature. This was done by heating the 9 cubes all together in an electric oven used for ceramic purposes (at faculty of Art) at a steady rising heating temperature of 50^0C per hour up to 1000^0C, then the cubes were kept at this temperature for a duration of 60 minutes, then cooled down to room temperature. They were then tested same as those exposed to fire.

Testing instruments and methods:

Standard Schmidt hammer was used for the Rebound Number tests, and for the UPV test, a digital pulse measuring device as shown in Figure2 was also adopted. The compressive strength testing was done under a digital compression machine, all instruments from Control manufacturer. All tests were carried out according to ASTM specifications.

Results and discussion:

Effect of firing exposure duration on concrete unit weight:

Figure 5 shows the relationship between unit weight of the concrete cubes and duration of fire for all mixes cooled in air, while Figure 6 shows the same relationship for all the mixes cooled in air and water. The unit weight decreases as the exposure time increases, the unit weight for the cubes quenched in water are higher than those cooled in air due to the added weight of water penetrated in to the cubes during cooling process in water. A best fit curve which is a polynomial curve is plotted for the unit weight (w) in terms of firing exposure duration (D) with very good correlation R^2=0.8134 as shown in figure 6:

$$w = 0.0384D^2 - 5.0674D + 2357.4 \quad \text{.....}(1)$$

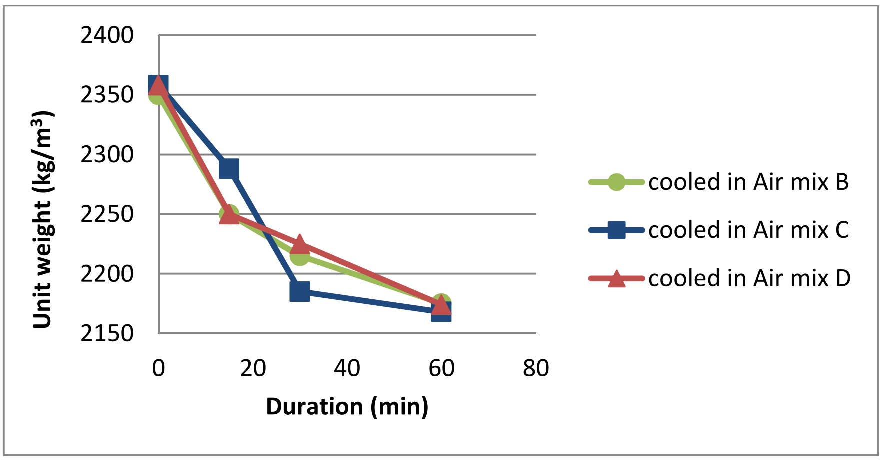

Figure5 Concrete unit weight vs. duration for all mixes cooled in air

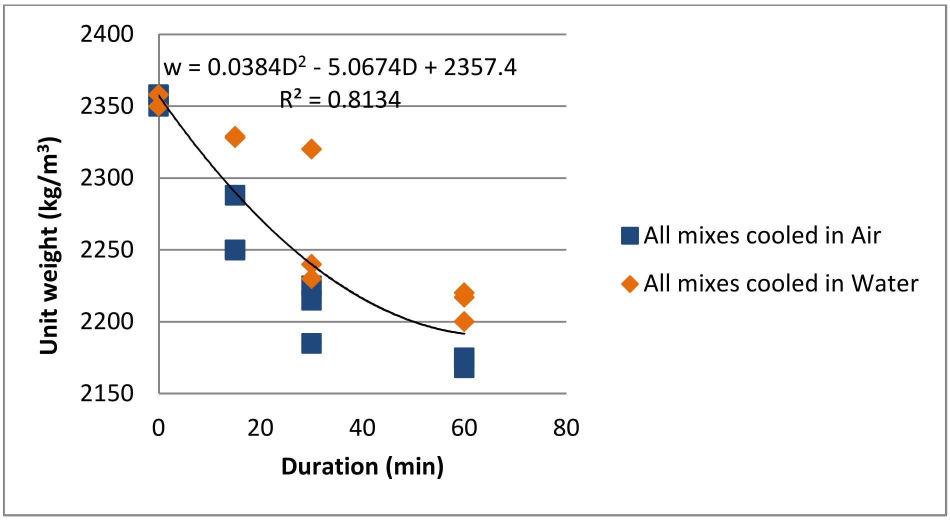

Figure6 Concrete unit weight vs. duration for all mixes cooled in air and water

Effect of heating exposure duration on concrete unit weight:

The weight loss for the cubes heated steadily up to 1000^0C and kept constant at that temperature for one hour was much more compared to the cubes exposed to fire for one hour duration, the losses were about 18% in the former and 8% in the later. This is because of the heating process which has taken more than 20 hours to reach the 1000^0C hence the cubes have suffered intensive cracking and disintegration.

Effect of firing exposure duration on concrete strength:

Figures 7 and 8 show the cubes compressive strength for different exposure durations of fire for all mixes for both methods of cooling in air and in water, respectively. They all show similar pattern of strength decrease as the exposure time is increased, and the cubes quenched in water show more reduction in strength compared to those cooled in air. The reduction of concrete compressive strength for the mixes tested is ranging from 43 to 55% for 60 minutes fire exposure when cooled in air and from 52 to 64% reduction in strength when cooled in water as shown in Table 3. With regard to cubes heated steadily up to 1000^0C, and kept constant at that temperature for 60 minutes, the decrease was much more than those exposed to 60 minutes duration of fire, as they lost from 82 to 92% of their non-heated strength. These results agree well with results of previous experimental tests [11, 12, 14, 19, 20].

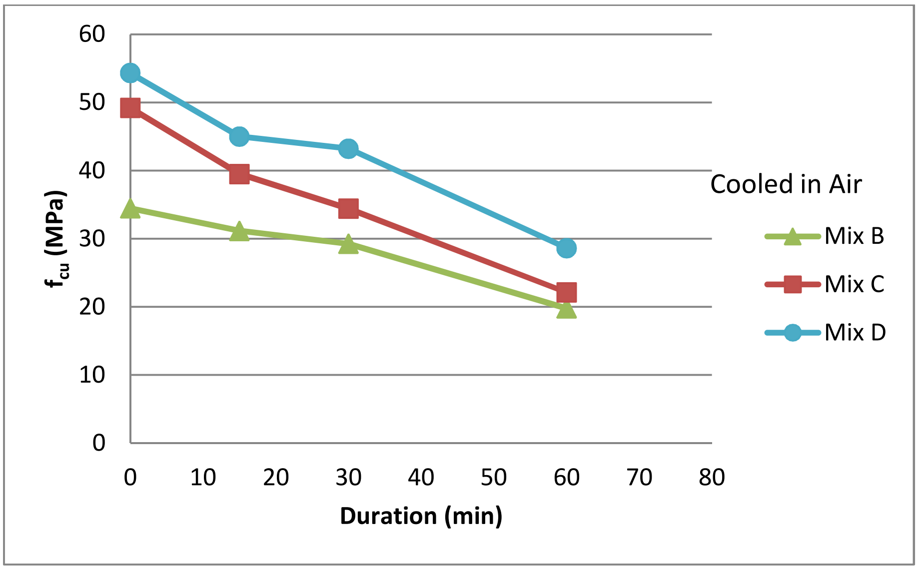

Figure7 Strength vs. duration time for all mixes cooled in air

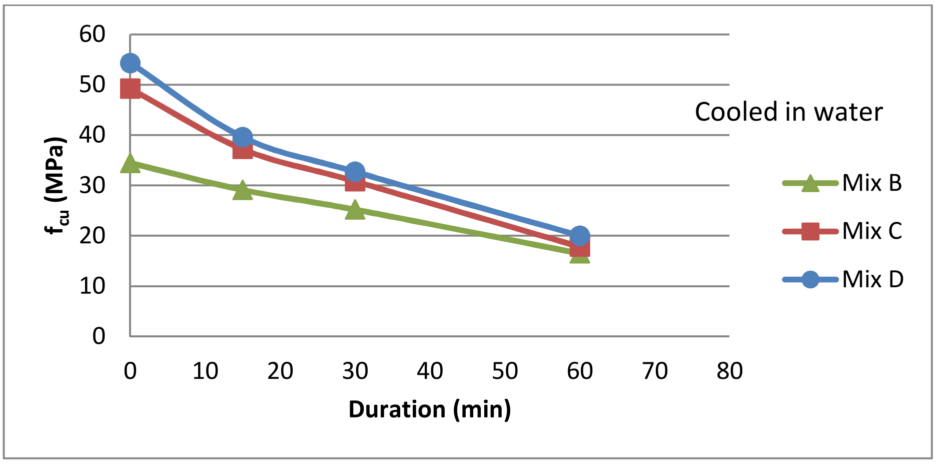

Figure 8 Strength vs. duration time for all mixes cooled in water

Table 3.Strength reduction ratios for all mixes cooled in air and water

Mixes	Firing time (min)	f_{cu} (cooled in air) MPa	Strength reduction ratio %	f_{cu} (cooled in water) MPa	Strength reduction ratio %
Mix B	0	34.45	0	34.45	0
	15	31.14	10	29.10	16
	30	29.24	15	25.19	27
	60	19.77	43	16.50	52
	Steady heat	2.91	92	-	-
Mix C	0	49.20	0	49.20	0.0
	15	39.50	20	37.20	24
	30	34.40	30	30.80	37
	60	22.10	55	17.80	64
	Steady heat	4.17	92	-	-
Mix D	0	54.3	0	54.30	0.0
	15	45.00	17	39.60	27
	30	43.20	20	32.70	40
	60	28.60	47	20.00	63
	Steady heat	6.91	87	-	-

The strength reduction of concrete exposed to heating is well documented and known [21]. When it starts, water evaporation occurs from the pores close to the surface, then after temperature of 100^0C the water evaporates at a faster rate and from pores away from the surface. Between 150 to 300^0C concrete may exhibit some regain of strength, then further reduction in strength as the temperature rises. Mechanical and chemical changes occur in the microstructure of the concrete causing decomposition of cement paste, dehydration of the cement paste, and expansion of the aggregate reducing the bond between the aggregate and cement paste. At higher temperatures (between 600 to 900^0C) further decomposition of the cement paste occurs and the lime-stone undergo de-carbonation [21]. Quenching in water (rapid cooling) causes thermal shock and causes higher reduction of strength [22] as it is well indicated from the results. Very fine concrete cracking starts early at 15 minutes exposure duration to fire , however at 60 minutes duration the cracks become much wider and randomly distributed at the surface of the concrete cube, especially more apparent at the surface directly exposed to fire. The cubes heated steadily up to 1000^0C showed more cracking and disintegration at the surface and spalling at the cube corners. Figures 9 and 10 show some of the fired samples before and after testing respectively.

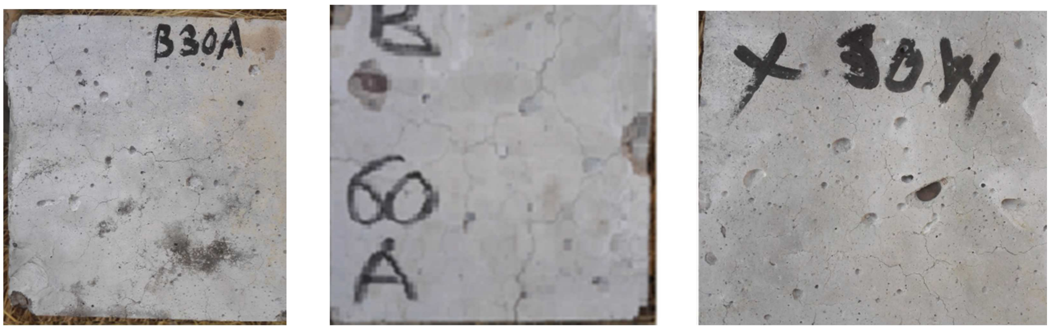

Figure 9 Concrete cubes cracking before testing

Figure 10 Concrete cubes after testing

Residual strength of concrete after exposure to fire:

After exposure to high temperature heating or fire it is important to know the residual strength (R_S) of the concrete in terms of its original strength. Figures 11,12 and 13 show the residual compressive strength of the concrete cubes vs. duration of fire for the mixes B,C and D respectively for both cooling methods. The same correlation for all the types combined is presented in Figure 14. For all the concrete strength levels the residual strength after 60 minutes exposure to fire is ranging from 35 to 55% of the original strength without fire exposure. The relationship between the residual compressive strength of concrete and the firing duration can be well represented by the following straight line equation with high correlation coefficient R^2 = 0.8892 as shown on figure 14:

$R_s = -0.0087d + 0.9757$ .... (4)

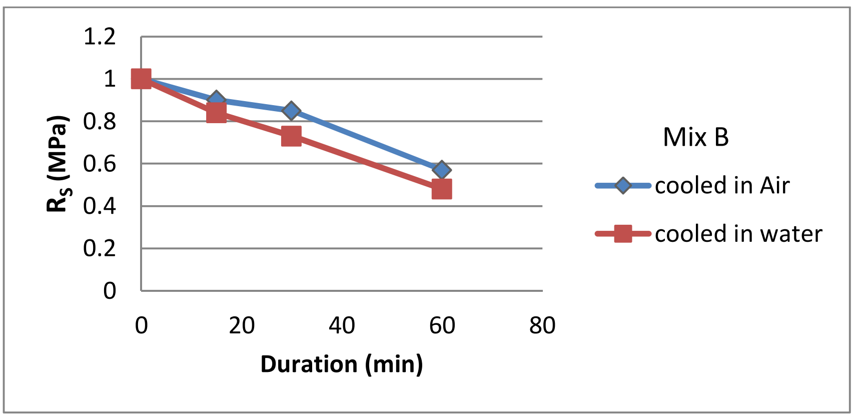

Figure11 Residual compressive strength vs. duration - mix B

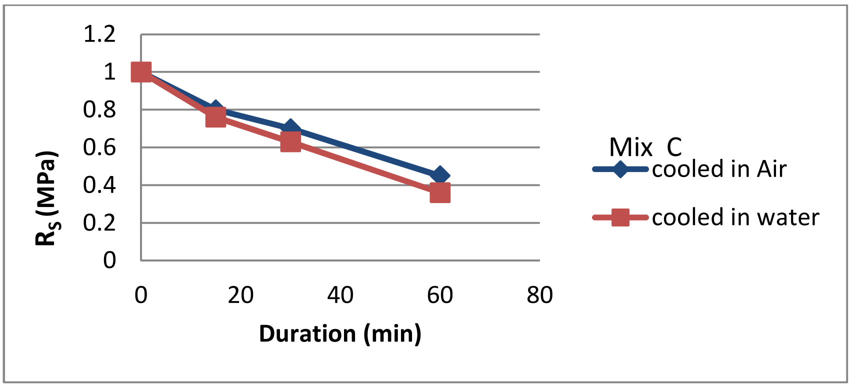

Figure12 Residual compressive strength vs. duration- mix C

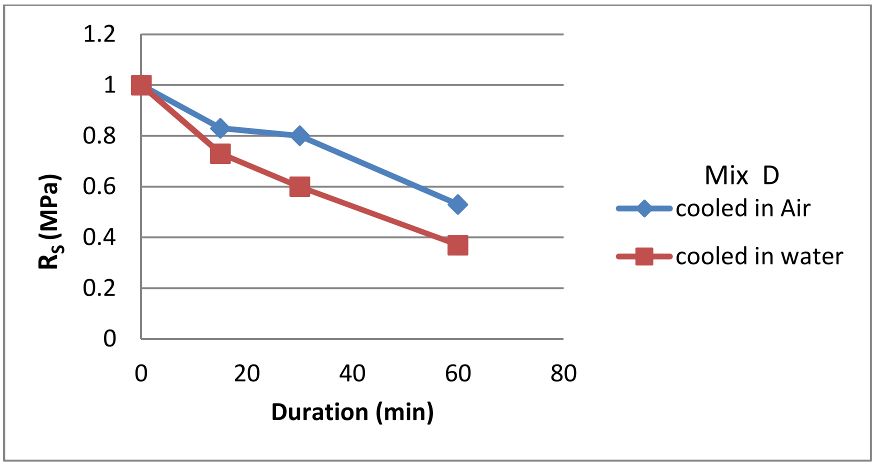

Figure13 Residual compressive strength vs. duration- mix D

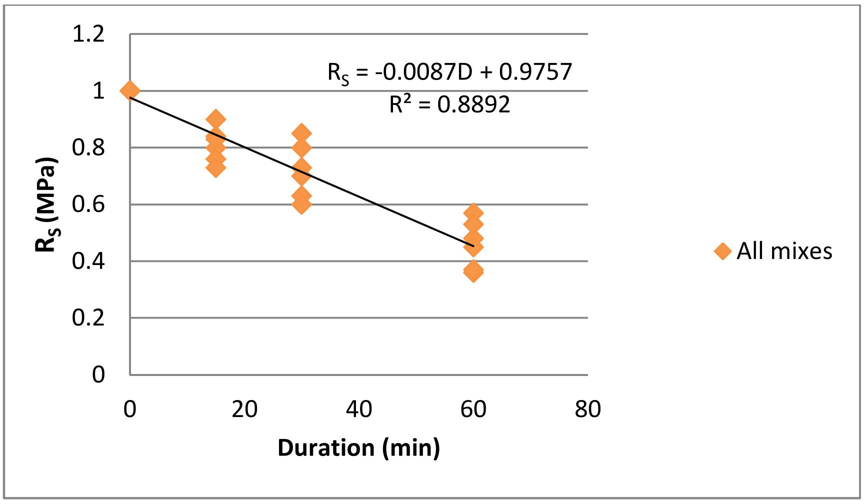

Figure14 Residual compressive strength vs. duration-all mixes

Hammer rebound number and concrete strength:

Figures 15 and 16 show the relationship between destructive test of cube compressive strength and non-destructive results by the hammer test rebound number for all the mixes for all durations cooled in air and in water, respectively. Figure 17 shows the relationship for all types for both kind of cooling. The RN increases as the cube compressive strength increases, the relationship between the concrete compressive strength and RN for all the mixes tested can be represented by the following straight line equation with excellent correlation $R^2 = 0.9717$ as shown on figure 17:

f_{cu}= 1.7541RN-26.686……………………………………..(2)

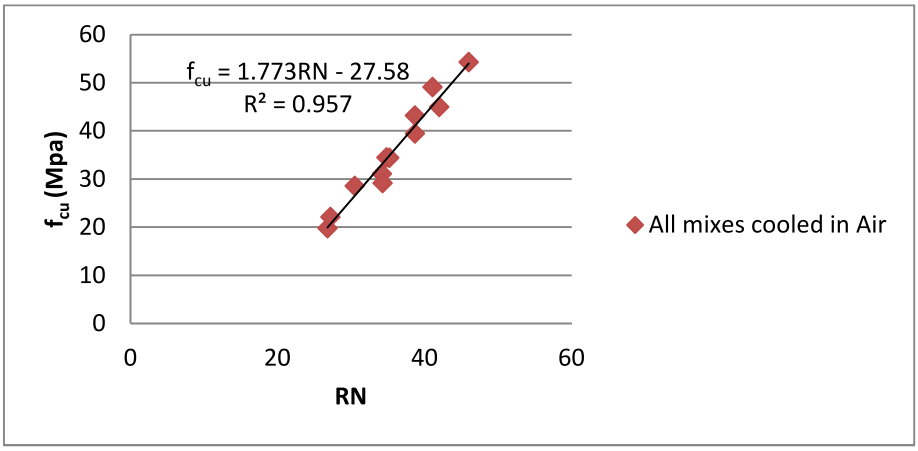

Figure15 Concrete Strength vs. RN for all mixes cooled in air

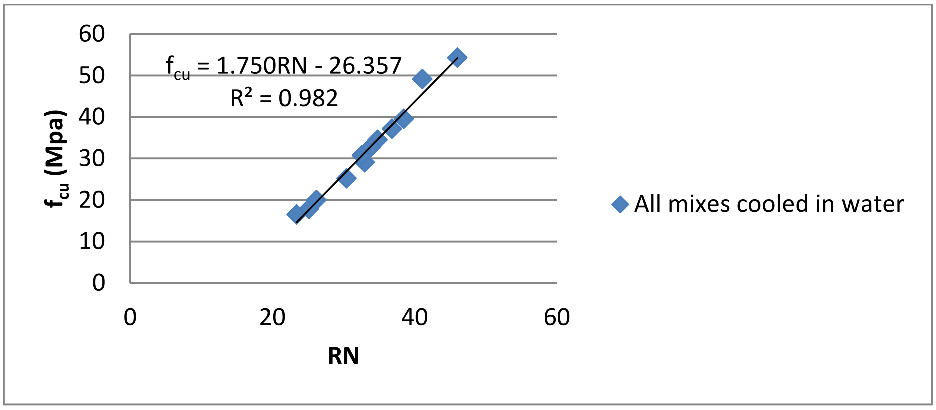

Figure16 Concrete Strength vs. RN for all mixes cooled in water

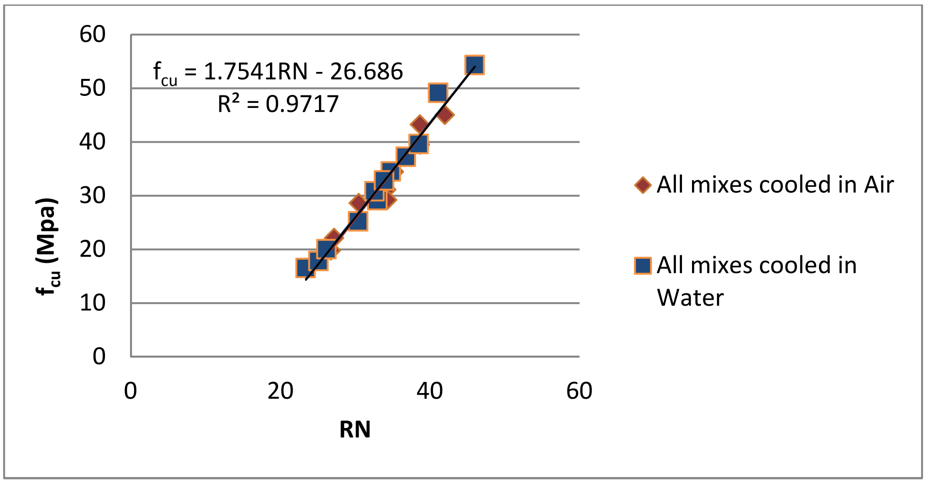

Figure17 Concrete Strength vs. RN for all mixes cooled in air and water

Ultra Sonic Pulse Velocity and concrete strength:

Figures 18 and 19 show the relationship between cube compressive strength and the UPV test for all the mixes for all durations cooled in air and in water, respectively. The same correlation is presented in Figure 20 for all mixes and for both types of cooling.

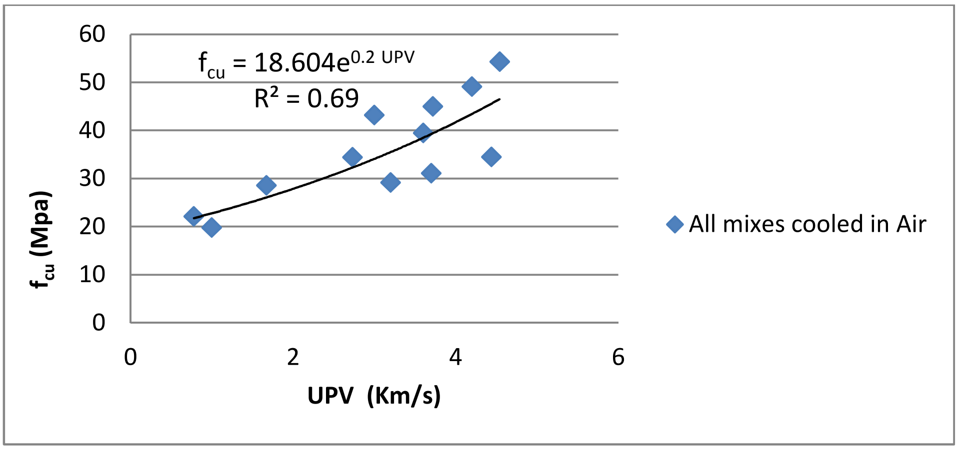

Figure18 Concrete Strength vs. UPV for all mixes cooled in air

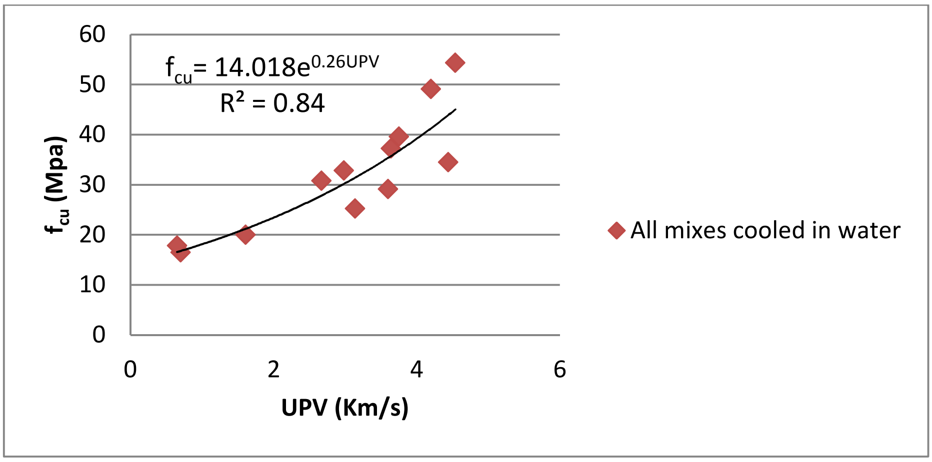

Figure19 Concrete Strength vs. UPV for all mixes cooled in water

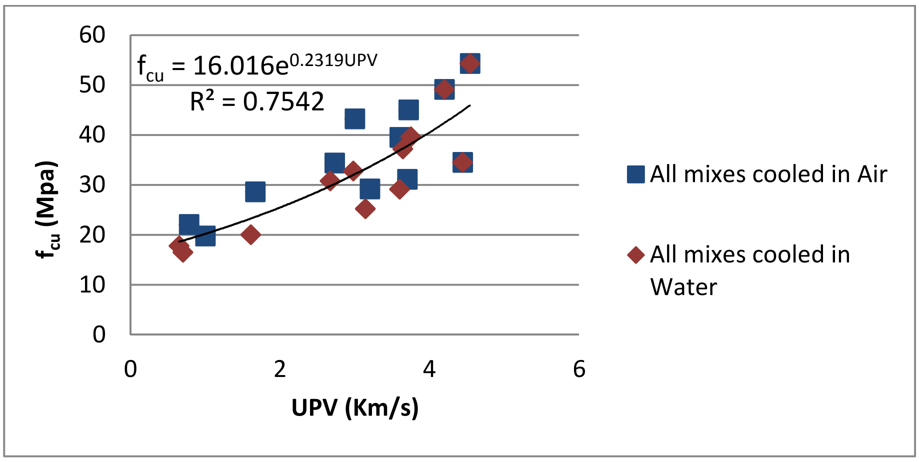

Figure20 Concrete Strength vs. UPV for all mixes cooled in air and water

In general UPV increases with the increase in compressive strength, however the results are scattered predicting worthless correlation between the predicting cube strength and UPV. Results also indicated that as fire exposure duration increases the correlation becomes less and less. The relationship between the predicting concrete compressive strength and UPV for all the mixes tested can be represented by the following exponential equation with lower correlation compared to other relationships, R^2 = 0.7542 as shown on figure 20.

$$f_{cu} = 16.016e^{0.2319UPV} \quad \text{……………………………………… (3)}$$

Abdulla and Abdulkadir [7] have conducted experiments on concrete of different strengths and have shown that using combined NDT methods (RN and UPV) gives better correlation between predicting cube compressive strength and the combined tests methods. The aforementioned analysis was exploited in the current investigation for all mixes and a good correlation factor was obtained R^2 = 0.971 with the following equation:

$f_{cu} = 0.018\ RN^{1.849}\ e^{0.982UPV}$ ………………………………….. (5)

where R^2 = 1 – (Residual Sum of Squares) / (Corrected Sum of Squares)

Conclusions:

From the results of this investigation in which destructive and non destructive tests were carried out on concrete cubes with three different strength levels after exposure to different firing exposures, the following conclusions may be drawn:

1. The unit weight and compressive strength of concrete decrease as the firing exposure duration increase, the trend is similar for both low strength concrete (Mix B) and high strength concrete (Mix D).
2. Non destructive test using hammer test gives good indication of strength of concrete after exposure to fire for the duration up to 60 minutes, the correlation with destructive compressive strength test is promising.
3. Non destructive test using Ultra Sonic Pulse velocity test gives reasonable indication of concrete compressive strength exposed to fire, the correlation is becoming less with high exposure durations.
4. After about 60 minutes of fire exposure duration, the residual strength of concrete compressive strength is about 40% of its original strength.
5. The cubes heated steadily up to 1000^0C showed significant reduction in weight, compressive strength and residual strength.

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