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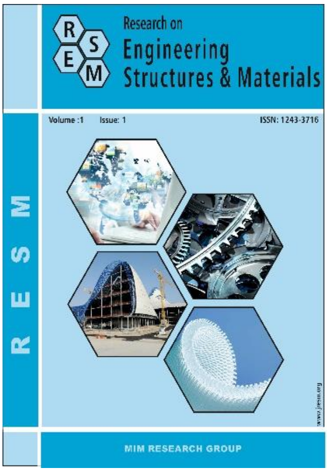

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Research Article

Strength evaluation of a fire damaged concrete slab: combined correlation approach

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Abstract

Strength evaluation of fire damaged concrete is not well studied although fire damaged concrete is encountered in many settings. There are limited studies that investigate the effect of physical properties on the strength of fire damaged concrete. In this paper, a fire damaged concrete slab element is evaluated based on non-destructive (rebound hammer and impact pulse velocity) and destructive (core and porosity) testing. Two correlation models are developed to assess the compressive strength of the slab element. The first model correlates the corrected core compressive strength to rebound number, impact pulse velocity and porosity. The second model correlates the corrected core compressive strength to rebound number and impact pulse velocity. Both correlation models are based on Pearson's statistical approach. The two correlations are compared based on William's modification of the Hotelling test and results indicate that rebound number, impact pulse velocity and porosity combined correlates more significantly to the corrected core compressive strength than rebound number and impact pulse velocity alone.

1. Introduction

Knowledge of the in-situ concrete properties is an important factor in understanding the integrity of a structural element in an existing or a newly constructed structure. Assessing the compressive strength property of concrete is important to decide on possible recommendations for repair or demolition and to design rehabilitation systems required to maintain the structural integrity of a structure [1].

Concrete strength is determined through various methods including non-destructive and destructive testing. Evaluating and assessing concrete compressive strength through correlations between non-destructive and destructive testing have been established by many previous researchers. Examples include works of [2], [3] and [4]. [2] provided a recommendation and guidance on the combination of different non-destructive and destructive tests in order to increase the accuracy of estimating the in-situ concrete strength. SONREB method was developed by RILEM Technical committee to establish a combination between rebound index and pulse velocity. This method was based on the application of a correction factor between a reference concrete (for calibration) and the concrete under test. A final calibration factor was calculated based on theoretical and

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experimental data. It was concluded that the SONREB method is accurate as long as 90% of the values of the non-destructive test measurements conform to the destructive test measurements. [3] correlated Schmidt hammer testing and destructive core testing based on experimental results. Findings of [3] indicate that Schmidt hammer testing alone is not reliable for strength evaluation of concrete structures; correlations between Schmidt hammer and core testing is often required to make a sound evaluation. [4] correlated rebound hammer number, ultrasonic pulse velocity and core test based on Pearson's and Spearman's approaches, which gave good and reliable results.

Non-destructive tests are important methods to estimate concrete strength in fire damaged structures. This is attributed to the fact that fire damaged structures are structurally weak and minimal cores shall be taken in order not to diminish further the structural integrity of the structure under assessment. However; for fire damaged concrete, correlations between non-destructive tests and core tests alone does not provide reliable estimates of concrete strength; this is due to many other factors that can influence the strength of fire damaged concrete [2]. As concrete is exposed to fire, the percentage of voids increases and as a result the strength of concrete will decrease accordingly.

Examples of strength evaluation of fire damaged concrete include works of [5], [6], Dilek [7], [8] and [9]. [5] concluded that the properties of the constituent of material in RC beams, concrete and steel, progressively decrease by increasing temperature. [6] found that the shear strength of simply supported RC beams highly depends on the fire durations and thickness of concrete cover.

[7] assessed a fire damaged wall at the foundation level of a structure. The assessment included a non-destructive evaluation through ultrasonic pulse velocity test and several destructive core tests removed from the damaged wall. Dynamic Young's modulus and an air permeability index of 25 mm thick disks sawed from the cores were also determined and analysed. Non-destructive test results identified the presence of distressed layers of near-surface concrete, but could not provide information on the characteristics of these damaged layers. While destructive core testing did not identify the effects of the weakened layers of concrete. Loss of Young's modulus for the damaged layers of concrete was noticed in comparison to the Young's modulus of non-damaged concrete, and a significant increase in the air permeability of the fire exposed concrete surface was found. It was concluded that for thin layer damaged concrete core testing is not significant, while assessing dynamic modulus and air permeability index (API) tests proved to be more reliable.

[8] discussed a renewed version of hammer-drilling method to evaluate fire damaged concrete. This method was based on continuously monitoring the pulse transmission of the hammer-drill method to evaluate the mechanical properties of damaged concrete. The method analysed the amplitude of the reflected waves, which provides information on the local acoustic resistance of concrete, and calculates the time of flight of the pulses propagating from the tip of the drill-bit to a fixed ultrasonic receiver on the surface of the concrete member. It was concluded that amplitude of the transmitted pulse is strongly influenced by hard aggregate pebbles and is poorly sensitive to thermal damage which makes this parameter unsuited to this particular case. However, the velocity of the transmitted pulse was not influenced by coarse aggregate, and proved to be a sensitive indicator to the conditions of fire damaged concrete.

[9] addressed the effect of burning by fire flame on the behaviour and load capacity of rectangular reinforced concrete beams. Ultrasonic pulse velocity and rebound number tests were used to assess the impact of fire on the beams. Results showed reductions in

both ultrasonic pulse velocity and rebound number for beams, and that sudden cooling of concrete causes additional strength loss of concrete (air cooling vs water cooling). Experimental results also indicated that the crack width in concrete of fire damaged beam are higher than beams subjected to identical loads. Load deflection were more levelled signifying softer load-deflection behaviour than that of control beams, which were attributed to early cracks and low modulus of elasticity.

A thorough review of the literature indicates that strength evaluation of fire damaged concrete, which takes into account physical concrete properties, is not well studied although physical properties of concrete can highly influence the strength of fire damaged concrete. In this paper a correlation between porosity, impact pulse velocity, rebound number and core testing is established for fire damaged concrete slab and is statistically compared to the correlation excluding porosity. Correlation coefficients are calculated using Pearson's statistical approach.

2. Experimental

Slab element of a five-story residential structure that was subjected to an extensive fire, lasting for five hours, with a predicted maximum temperature of 500 °C, was studied. Destructive and non-destructive testing were recorded prior to demolition of the structure. Non-destructive tests included rebound hammer and impact pulse velocity, destructive tests included coring and porosity. Destructive tests consisted of the extraction of 30 cores from severally distributed points of the slab. Cores were tested in the laboratory for compressive strength and porosity. Non-destructive tests were carried out prior to the extraction of cores, and at the same locations of the extracted cores. Each non-destructive test was repeated at least twice to ensure repeatability and average values were reported.

2.1. Review of Destructive and Non-Destructive Testing Methods

Destructive and non-destructive testing methods for determining in-situ concrete strength are briefly presented. As well as the method for determining the percentage porosity of concrete.

Core testing is the most direct and accurate method in estimating the concrete strength in concrete structures. Core specimens are extracted from structural elements, and conditioned, then crushed to evaluate the compressive strength of the core. Before testing, cores are trimmed at the ends so that they are flat and perpendicular to the longitudinal axis of the core. The core ends are caped with a high alumina cement mortar, and tested in a dry state. Scatter in core test results can be found and is mainly attributed to variations in concrete characteristics and site stress distributions [4].

Rebound hammer test is the simplest way to estimate the concrete compressive strength. It is characterized by being the least expensive test, developing the smallest amount of structural damage, and practicality. Rebound hammer test only investigates the surface layer of concrete, and results might not represent the interior of the concrete. For that, rebound hammer is not an entirely accurate method. The surface of concrete is impacted by a steel hammer via a spring, and concrete compressive strength is estimated through the surface hardness rebound value. The amount of lost Kinetic energy during the impact of the steel hammer is measured, and this loss of energy is correlated with the strength and rigidity of concrete [10].

Impact pulse velocity test is used to determine the velocity of propagated waves along a known distance in a concrete specimen, two transducers are placed along that distance to calculate the velocity. The transducers are placed on opposite sides of the concrete element (direct transmission), adjacent sides of the concrete, or on the same face of the concrete element. For best results, the two transducers are place directly on opposite sides, so loss of sensitivity and accuracy is avoided. An appropriate coupling agent is placed on both the transducers face, and the concrete surface. The faces of the transducers are pressed firmly to the concrete surface until a stable transit time is displaced. The transit time is measured and the wave velocity is calculated. These values are used to correlate the properties of concrete through curves provided in the test device. Impact pulse velocity is affected by water/cement ratio, moisture content, presence of reinforcement, and cracks present in concrete.

Porosity test is used to calculate the percentage of voids present in a concrete specimen. Voids in fire damaged concrete occurs when water content reaches boiling point and evaporates through concrete, creating voids while escaping from entrapment. Percentage of voids increases proportionally with the increase in the exposure time of fire. Porosity index is an important factor to assess the degree of damage in a fire damaged structure.

2.2. Testing Program

Rebound hammer, impact pulse velocity, destructive core and porosity tests were carried out using instrumentation and testing procedures typically adopted in practice and following American Standard Testing Methods ([11], [12], [13], and [14] respectively).

Tests were carried out in severally distributed points along the slab. A reference grid system was created to uniformly distribute the testing locations on the slab. The grid system split the slab to 30 cells, and a grid naming was used to identify each test location as shown in Figure 1 below.

A precise survey was done using the ground penetrating radar test to locate the longitudinal and transverse reinforcing steel bars, before commencing with the tests. In this way, it was possible to avoid steel bars during core extraction.

Non-destructive rebound hammer test was carried out first, and ten readings were taken per cell. The mean rebound hammer value was recorded. Impact pulse velocity was measured for each cell, and a minimum of two readings were taken. The mean value of the two readings was recorded. One core was extracted from each cell (denoted by a black circle in Figure 1), and the compressive strength of each core was measured. Finally, porosity of each core was investigated by calculating the percentage of voids in the extracted core. Testing program is summarized in Table 1 below.

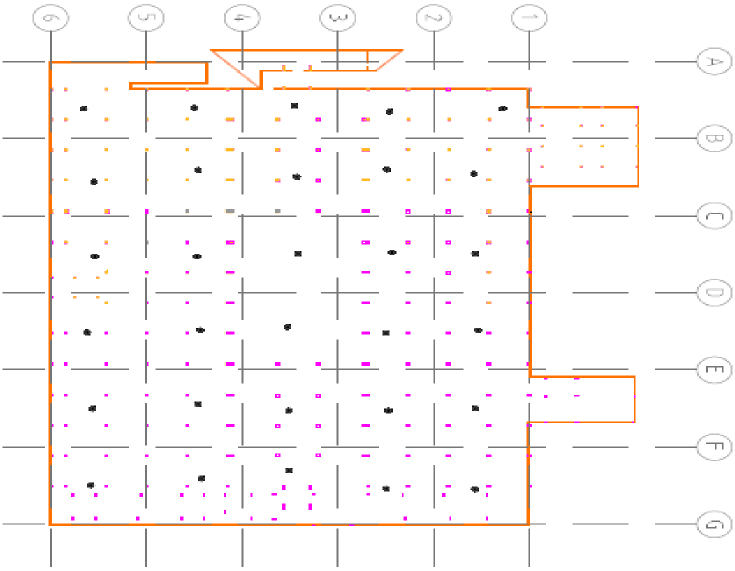

Fig. 1. Testing locations

Table 1. Testing program

Test	Number of Tests Performed
Core	30
Impact Pulse Velocity	30
Rebound Hammer	30
Porosity	30

2. Results and Analysis

Core compressive strength results were corrected to account for length to diameter ratio, diameter, moisture conditions and drilling factors, as per the recommendation of [15]. Extracted cores measured 10 cm in diameter and 20 cm in length and were soaked for 48 hours prior to crushing. Corrected core compressive strength values were calculated by multiplying each core compressive strength by a factor of 1.16. Non-destructive and destructive testing results are summarized in Table 2 below.

Coefficient of variation (CV) for each studied parameter was calculated. Higher CV values were found for the porosity parameter (27%) and rebound number (16%), while impact pulse velocity and core compressive strength returned lower values of CV (11% and 14% respectively). Usually it’s normal to expect some scatter in the results taking into account the extent of fire reached to different parts of the slab, the within tests variability and the within member variability of concrete compressive strength. Overall variability of core compressive strength data is considered acceptable if compared to the value suggested by [15] of 13%.

Table 2. Destructive and non-destructive testing results

Grid	**Corrected Core Compressive Strength (*MPa*)**	**Rebound Number**	**Impact Pulse Velocity (*km/s*)**	**Porosity**
AB12	18.2	43	1.4	0.0773
AB23	24.1	49	1.6	0.053
AB34	21.2	38	1.34	0.0687
AB45	30.3	66	1.75	0.0211
AB56	24.5	50	1.55	0.0531
BC12	26.2	60	1.67	0.0413
BC23	19.4	47	1.3	0.0718
BC34	22.5	44	1.4	0.0698
BC45	26.1	56	1.39	0.0447
BC56	23.2	50	1.44	0.0616
CD12	22.7	57	1.4	0.0629
CD23	20.9	38	1.38	0.0773
CD34	24.6	59	1.53	0.0498
CD45	23.5	57	1.48	0.0564
CD56	27.1	44	1.35	0.0438
DE12	26.4	61	1.42	0.0438
DE23	19.4	38	1.2	0.0885
DE34	19.8	48	1.32	0.0902
DE45	22.3	50	1.52	0.0704
DE56	21.2	51	1.3	0.0773
EF12	18.7	45	1.22	0.0824
EF23	20.5	45	1.38	0.0768
EF34	24.2	39	1.67	0.0566
EF45	19.7	46	1.42	0.0777
EF56	25.3	52	1.76	0.0551
FG12	19.1	44	1.57	0.0655
FG23	22.9	45	1.45	0.0623
FG34	27.5	51	1.86	0.0444
FG45	24.2	53	1.54	0.0525
FG56	17.1	36	1.62	0.0919

Three graphs showing the relation of corrected core compressive strength, rebound number, impact pulse velocity and porosity respectively are shown in Figure 2 below.

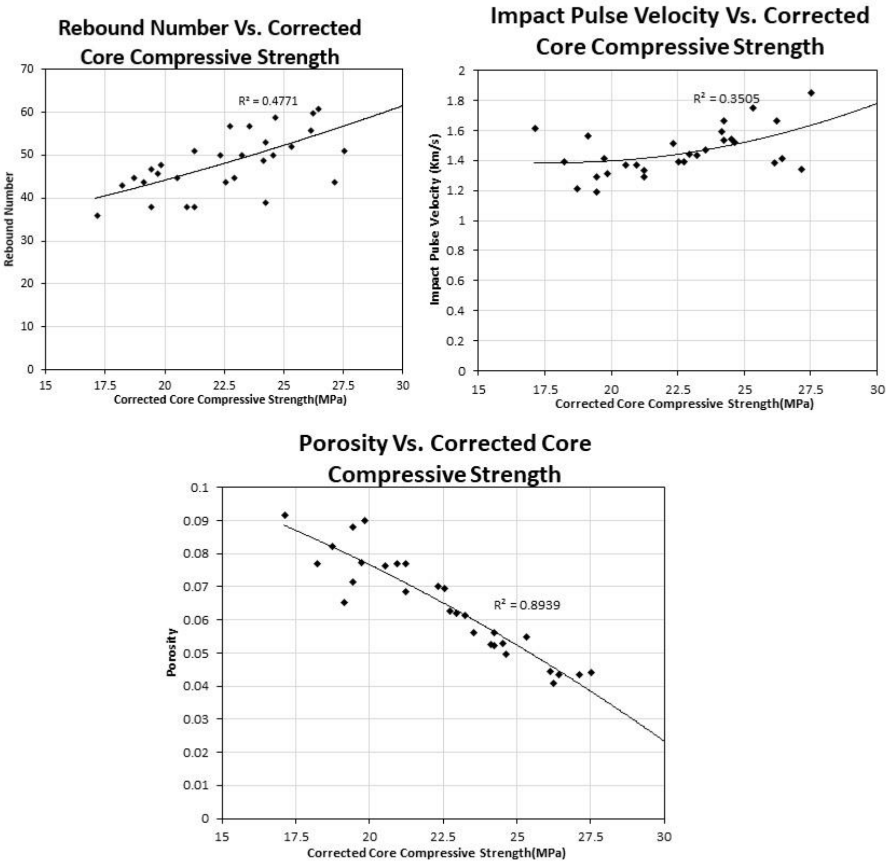

Fig. 2. Graphical representation of the results

2.1. Parson's Correlation Coefficients

To better assess the correlation between non-destructive and destructive test results, Pearson's correlation coefficients were determined. The aim is to find two relations between the studied variables in the forms:

$$f_c = a(RH)^b (V)^c (P)^d \tag{1}$$

$$f_c = a(RH)^b (V)^c \tag{2}$$

where: f_c – corrected core compressive strength; *a, b, c* and *d* – Pearson's correlation coefficients; *RH* – rebound number; *V* – impact pulse velocity; *P* – porosity.

Pearson's correlation coefficients along with some statistical parameters for the case including porosity in the correlation and the case excluding porosity from the correlation respectively are presented in Tables 3 and 4 below.

Table 3. Pearson's correlation coefficients (including porosity)

	Coefficients	**Standard Error**	**t-Stat**	**P-Value**	**R square**
a	5.6	0.31	5.48	9.32E(-6)	0.82
b	0.08	0.10	0.76	0.45	
c	0.03	0.13	0.22	0.83	
d	-0.38	0.06	-6.10	1.90E(-6)	

Table 4. Pearson's correlation coefficients (excluding porosity)

	Coefficients	**Standard Error**	**t-stat**	**P-Value**	**R square**
a	2.67	0.45	2.20	0.03	0.57
b	0.51	0.12	4.24	2.00E(-4)	
c	0.45	0.17	2.58	0.015	

It can be noted from Tables 3 and 4 above that statistical parameters vary widely between the two correlations. Standard error returned smaller values for the case including porosity in the correlation. P-values and t-stat parameter varied between coefficients of the two correlations. For instance, the intercept (a) in the correlation including porosity returned higher value of t-stat parameter and lower P-value than the intercept (a) in the correlation excluding porosity; whereas the rebound number coefficient (b) in the correlation including porosity returned a lower value of t-stat parameter and a higher P-value than the rebound number coefficient (b) in the correlation excluding porosity. Thus a general conclusion from the comparison of those statistical parameters cannot be made. The correlation including porosity returned higher R-square value (0.82) than the correlation excluding porosity (0.57). However; conclusions about the better correlation cannot be made by directly comparing R-square values.

2.2. Statistical Comparison Between the Two Correlations

Direct comparison between statistical parameters may not be always indicative on whether two correlations are significantly different from one another or not. To test whether the two correlations are significantly different, the correlations are transformed using William's modification of the Hotelling test with a significance level of 0.05. The r value is distributed as t with *(n-3)* degrees of freedom [16]. The following null hypothesis is tested,

H_0: The correlation including porosity as a parameter in evaluating strength of fire damaged concrete is the same as the correlation excluding porosity. Results of William's modification of the Hotelling test are summarized in Table 5 below.

Table 5. Williams modification of the Hotelling test

r_{1-2}	r_{2-3}	r_{1-3}	**t(n-3)**	**Critical t value at 0.05 significance level**
0.8	0.75	0.91	1.96	1.7

where: r_{1-2} – correlation between porosity, rebound number and impact pulse velocity ; r_{2-3} – correlation between corrected core compressive strength, rebound number and impact pulse velocity; r_{1-3} – correlation between corrected core compressive strength, rebound number, impact pulse velocity and porosity; $t(n-3)$ – William's modification parameter.

Results of the Williams modification of the Hotelling test indicate that William's modification parameter is statistically significant at a 0.05 significance level. Thus the null hypothesis should be rejected and the correlations are significantly different at a 0.05 significance level. It can be concluded that, rebound number, impact pulse velocity and porosity combined correlate more significantly to the corrected concrete compressive strength of a fire damaged slab than rebound number and impact pulse velocity combined alone.

Conclusions

In this paper two strength evaluation models for a fire damaged concrete slab were studied. Strength evaluation models were based on correlations between non-destructive (rebound hammer and impact pulse velocity) and destructive (core and porosity) tests. The correlation coefficients were calculated using Pearson's correlation approach. A statistical comparison of the two correlations was conducted using William's modification of the Hotelling test. Based on the experimental findings the following conclusions could be made:

- Comparison between the strength evaluation models indicates that the two models are statistically different and the correlation model which includes porosity as a parameter to evaluate the strength of fire damaged concrete correlates more significantly to the corrected core compressive strength.
- Correlations between non-destructive and core testing alone may not be reliable in strength evaluation of fire damaged concrete.
- Introducing physical properties of concrete, such a porosity, may help increasing reliability of strength assessment of fire damaged concrete.

It should be noted that all correlations and analyses conducted in this paper are based on the destructive and non-destructive testing results conducted on a specific slab element of a five-story residential building that was subjected to an extensive fire. As a result, correlation models and results presented pertain to this structural element and may not be directly applicable to other fire damaged structural elements. However; findings and conclusions may be indicative on the general effect of physical properties of concrete, such as porosity, on the strength evaluation of fire damaged concrete.

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