LIMITATIONS IN USING NON DESTRUCTIVE TESTS FOR ASSESSMENT OF CONCRETE SUBJECT TO ELEVATED TEMPERATURE

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ABSTRACT

The behavior of members during fire, as part of a structure, is different from that exhibited by small unrestrained samples. Full scale fire tests are costly and, because fire cannot be controlled, data is sometimes lost during testing. In this investigation 1/5 scale model frames were prepared from normal strength, high strength, fiber reinforced, latex modified and lightweight aggregate concrete. After heating to 800 °C, with either a superimposed load or without any loading, the frames were assessed using Schmidt hammer and ultrasonic pulse velocity. The effect of fire on compressive strength was studied on companion cubes made from the same concrete types. It was found that the deterioration suffered by a member depends not only on the type of concrete, from which the frame was made of, but also on the type of member and stress state. The Schmidt hammer test is not suitable for assessing concrete after a fire, mainly because fire reduces the rebound number greatly and this in turn makes readings obtained using the conventional hammer invalid. Pulse velocity measurements reflected the internal damage suffered by members, but the results need to be interpreted in light of materials properties, restraint, visual examination and stress states of members within structures. Pulse velocity-compressive strength relationship was profoundly affected by fire. For example, a UPV reading of 3 km/sec would indicate a compressive strength of either 382 or 82 kg/cm^2, depending on whether the concrete has been or has not been subject to elevated temperature, respectively. This needs to be taken into account in recommended procedures for assessing structures after fire.

INTRODUCTION

Deterioration of concrete during exposure to elevated temperature, like that encountered during a fire, is the result of many complex factors including:

a) The thermo-mechanical process. The temperature gradients induce gradients of thermal dilation, which in turn generate tensile stresses perpendicular to the heated surface. Local strain incompatibilities occur between the cement paste and aggregate. The aggregate dilate until they are chemically degraded, whilst the paste shrinks due to drying.
b) The thermo-hydral process. This is associated with the transfer of mass (water in liquid or vapor phases and air). The partial evaporation of water due to temperature increases the vapor pressure in concrete pores. This pressure leads to mass transfer towards both the heated surface and the cooler center of the elements. The center of the sample may become with time saturated with condensed vapor and pressure is generated [1].
c) Phase transformations. Free moisture evaporates at 100 °C. At 350 °C calcium hydroxide is decomposed into lime and water vapor. At 500 °C, quartz aggregate is transformed accompanied by 1% increase in volume. At 600 to 700 °C cement paste starts to decompose and finally at 800 °C limestone aggregates calcine, leading to expansion and loss of carbon dioxide [2].

d) Stresses induced in reinforced restrained structural members [3]. An external load, even an eccentricity, may be generated during fire as a result of element dilation, constrained by other members within the structure [1].

Research into the behavior of concrete under fire has branched in several directions, all giving valuable information towards the understanding of the phenomenon:

1) Studying the effect of temperature on the residual mechanical properties and microstructure of small laboratory concrete samples (e.g. [4]-[10])
2) Suggesting new methods for assessing the fire damage to concrete (e.g. [11]-[14]).
3) Investigating the structural behavior under fire of individual full scale laboratory prepared members, in order to predict the effect of fire on their load carrying capacity and mechanical properties (e.g. [15]-[19])
4) Computer modeling of the effect of temperature on structural members, to produce equations for designing members for a certain fire resistance and/or to provide a numerical understanding of the effect of fire (e.g. [20]-[23]).
5) Studies combining aspects of 3 and 4 from above to verify a proposed model experimentally (e.g. [24]-[27]).
6) Full scale fire tests on one or more compartments in an experimental building to understand the behavior of different members and how restraint affects such behavior in a real fire (e.g. [28]).

In practice, engineers are usually called in after a fire to ascertain whether a reinforced concrete structure can be repaired rather than demolished. Assessment of structural integrity must be made and it usually involves visual observations supported by various tests that give an indirect indication on the condition of the concrete (e.g. Schmidt hammer, Ultrasonic pulse velocity and core tests), [14].

Schmidt hammer test is based on the principle that the rebound of an elastic mass depends on the hardness of the surface upon which it impinges, and in this case will provide information about a surface layer of concrete defined as no more than 30 mm deep. Many factors influence the test results including, cement type and content, coarse aggregate type, mass of member and its degree of compaction, surface type, age, rate of hardening, curing type, surface carbonation, moisture condition, stress state of the element and ambient temperature. The test is best used in assessing the relative quality of the concrete and no unique relationship exists between the rebound number, obtained from the test, and the compressive strength of the concrete [29].

Ultrasonic Pulse Velocity (UPV) is usually used in attempting to define the extent and magnitude of deterioration resulting from fire, mechanical frost or chemical attack [29]. The technique is based on detecting changes in amplitude, phase and direction of mechanical waves as they propagate through a concrete member [15]. Nasser and Lai [12] found that the within test variability of UPV was small. The relationship between UPV and compressive strength is not unique. It is known to be affected by the moisture content, age, density of concrete and type and quantity of coarse aggregate [30]. Therefore, for insitu investigations of structures, even where no accidents like fire have occurred, ACI 228.1R-95 [31] recommends that cores should be extracted, after an initial survey is carried using Schmidt hammer and/or UPV, in order to determine the in place strength of the concrete. Thereafter, a relationship, valid only for members in that particular structure, can be developed between the nondestructive techniques results and compressive strength. Unfortunately, being a poor thermal conductor, concrete in a structural member is affected by fire to varying degrees depending on the depth from the exposed surface. This makes the assessment of fire damage much more difficult [32].

Nassif et. al. [3] argued that the behavior of an unrestrained specimen during fire is expected to be different from that of a restrained structural member. They added that the behavior of real structures in a real fire is an area needing much work. Unfortunately, full scale tests are costly and because fire cannot be controlled, data is sometimes lost during testing [28]. Therefore, the second best option would be to scale down structures in order to carry out controlled elevated temperature tests on small models. Ng et. al. [33] scaled down individual uniaxially loaded columns and reported that, with care, it is possible to construct and test such models for fire tests.

In this investigation the author attempted to study the behavior of concrete, after exposure to 800 °C, in 1/5 scale reinforced concrete model frames using the most commonly used nondestructive test techniques (i.e. Schmidt hammer and Ultrasonic pulse velocity). The frames were prepared from five different mixes (i.e. normal strength (NSC), high strength (HSC), fiber reinforced (FRC), latex modified (LMC) and light weight aggregate (LWAC)). From each mix, two model frames and six standard cubes were prepared, giving ten model frames and thirty cubes in total. The frame consisted of a reinforced slab (width 600, length 600 and thickness 40 mm) resting on four reinforced concrete columns (cross section 100 x 100 and clear height 600 mm), which in turn were held at the bottom by four reinforced concrete ground beams (cross section 100 x 100 and clear span of 600 mm). One frame, from each concrete type, was loaded with thermal bricks during the heat cycle, whilst the other was unloaded. Three cubes from each mix were also subject to the elevated temperature regime. Weight, Schmidt hammer and UPV measurements were conducted on all members within each frame, whereas the compressive strength and UPV was determined for the cubes, before and after heating. The effect of heat on UPV - compressive strength relationship for the standard cubes was investigated. The aim was to try to understand the complex behavior of different concretes, used in the preparation of the model frames, when heated as part of the scaled down structure. It is hoped that the results presented herein will help with the development of a more rational procedure for the assessment of concrete in structures after a fire.

EXPERIMENTAL PROGRAM

Materials

Ordinary Portland cement was used throughout the investigation. Natural sand and crushed dolomite coarse aggregates, having maximum aggregate size of 15 mm, were used as fine and coarse aggregates, respectively. Tap water was used in mixing and curing of all test specimens. The superplasticizer used for the HSC mix was a Naphthalene Formaldehyde Sulfonate Type F. The latex used in the LMC mix was Styrene Butadiene Rubber Emulsion. Polypropylene fibers were used in FRC mix. LECA was used as an artificial lightweight aggregate for LWAC mix. Maximum aggregate size for the LECA was 14 mm. Typical sieve analysis of the LECA is presented in Table 1. The density of the LECA was 365 kg/m^3.

Table 1 Sieve analysis for LECA

Sieve No. (mm)	14	10	5	2.36
(%) Passing	99.5	80	9	0.5

Mix proportions and method of mixing special materials

The proportions for the concrete mixes used in this investigation are shown in the Table 2. All mixes had liquid/cement ratio = 0.51 except for the HSC mix. The quantity of cement was increased and water was reduced in the HSC mix. The cement was also increased in the FRC and LWAC to increase the mortar volume to try to maintain a reasonable workability. The fibers were added after all dry materials were mixed in FRC. Latex was added directly to the fresh mix for the LMC as the product data sheet recommended.

Table 2 Mix proportions for concrete mixes

Materials \ Mix Type	NSC	HSC	FRC	LMC	LWAC
Cement (kg/m^3)	350	550	410	350	440
Fine Aggregate (kg/m^3)	750	750	675	750	300
Coarse Aggregate (kg/m^3)	1000	1000	900	1000	
Water (L/m^3)	180	160	215	130	225
Superplasticizer (L/m^3)		12			
Fiber (kg/m^3)			0.910		
Latex (L/m^3)				50	
LECA (kg/m^3)					550
w/c	0.51	0.29	0.51	0.37	0.51

W+ Superplasticizer /C for H.S.C = 0.31 W+Latex/C for LMC = 0.51

Preparation of test specimens

A specially designed and manufactured wooden formwork was used for casting the model frames. A frame, still in formwork, is shown in Figure 1. The frame consisted of a reinforced slab (width 600, length 600 and thickness 40 mm) resting on four reinforced concrete columns (cross section 100 x 100 and clear height 600 mm), which in turn were held at the bottom by four reinforced concrete ground beams (cross section 100 x 100 and clear span of 600 mm). Frame members were simply reinforced. The slab was reinforced by 5 longitudinal bars in the two directions with a diameter of 3 mm, providing a cover of 5 mm in all directions. The columns and ground beams were reinforced with 4 longitudinal bars with a diameter of 4 mm confined using a square stirrups/ties placed every 100 mm, providing a cover of 5 mm (Figure 2). More details are shown in Figures 3 and 4. Two model frame specimens and six 150 mm standard cubes were prepared from each mix. The specimens were cured under wet burlap for 1 day, and then in air for 40 days before being transported to the furnace for exposure to elevated temperature (Figure 5).

Figure 1 Model frame formwork

Figure 2 Reinforcement details of columns and ground beams

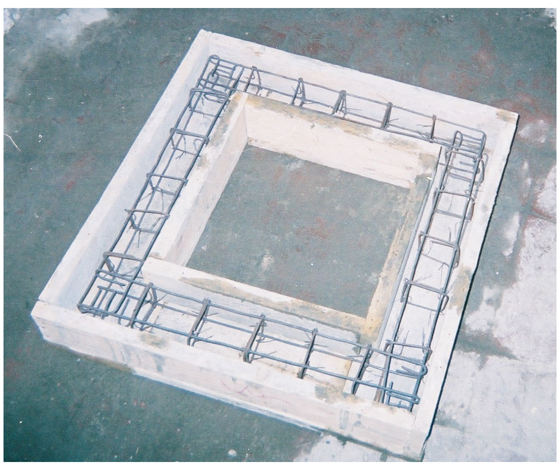

Figure 3 Sectional plan of ground beams

Figure 4 Elevation of model frame

Test techniques

Subjecting the samples to elevated temperature

The furnace used throughout the investigation was located in NATIONAL POTTERY CENTRE. The furnace had a plan area of 90X90 cm and a height of 120 cm, body made of steel, lined with a ceramic blanket, in which heaters were fitted closely from all sides (see Figure 6). The furnace heating rate was monitored and plotted in Figure 7. The target temperature of 800 °C was reached during a period of four hours. After that, the furnace automatically switched off. One hour later the doors were opened slightly to provide ventilation to the furnace. Room temperature inside the oven was reached 24 hours later. The heating rate of the furnace used in this investigation is much slower than the rate specified in BS EN 1363-1:1999 [34] for cellulose fire, and that encountered in hydrocarbon fire in which the temperature reaches 800 °C or 1100 °C in less than 15 minutes, respectively.

One model frame sample, from each mix, was subjected to elevated temperature in a loaded state. Load was in the form of 33 uniformly distributed thermal bricks (total weight 100 kg) to simulate a scaled down typical live load on the model frame (see Figure 8). The other frame was heated in an unloaded state (see Figure 9). Three cubes from each mix were also subject to temperature.

Figure 5 Transporting of specimens

Figure 6 Interior Furnace details

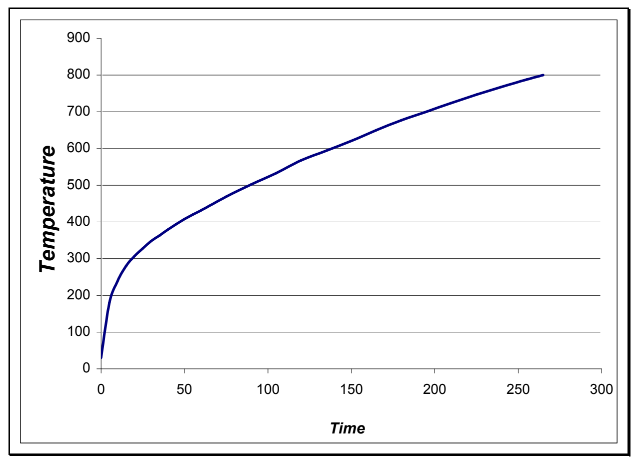

Figure 7 The time-temperature curve of the furnace

Figure 8 Loaded specimen with cubes prior to heating

Figure 9 Unloaded specimen prior to heating

Tests carried out on samples

Before being subjected to elevated temperatures all samples were weighed. In addition, rebound number of the slab, ground beams and columns for each model frame sample was estimated by taking twelve readings in each member in accordance with EC 203, Part 3: Section 8-2 [35]. The readings were taken vertically downwards for slab and horizontally for columns and ground beams. Ultrasonic pulse velocity measurements were also carried out on both cubes and model frame specimens in accordance with EC 203, Part 3: Section 8-3 [36]. The measurements were taken with the transducers placed on opposite sides of the position to be tested. Readings were taken for the four ground beams in the long direction, across the four columns and across the slab for each model frame sample. For the slab an additional measurement was made in the indirect position.

After being subjected to elevated temperature the samples were visually inspected. Weight, rebound number and ultrasonic pulse velocity measurements were again carried out on the cubes and frame samples where applicable. In addition, the cubes, which were not heated, and those subject to elevated temperature were tested for compressive strength. The reported values for compressive strength represent the average results of three specimens.

RESULTS AND DISCUSSION

Visual inspection of model frame samples after exposure to elevated temperature

The color of all specimens turned very light green (dark gray). However, the upper surface of the slab in loaded specimens did not show this color transformation. This may be attributed to insulation of slab with the thermal bricks used for load application. Deflection of the slab was obvious in loaded NSC, LWAC, and FRC samples. However, for loaded HSC and LMC no apparent deflection was noticed but cracks were seen in all corners of the slabs with an approximate length of 7 cm. For unloaded samples only small cracks were repeatedly observed especially in the slab and generally for the rest of structural elements (columns and ground beams).

Spalling of large pieces from reinforcement cover was noticed in the columns of unloaded FRC and NSC specimens especially after two days of air-cooling. Malhotra [4] suggested that the imposition of a stress during heating (load application) retards the development of cracks in a specimen, which would be free to extend in an unstressed specimen. The fact that some spalling occurred during cooling suggests that the reformation of calcium hydroxide by lime hydration, which is accompanied by expansion, may be responsible for this observation. The fiber content in the current study was approximately 1% by volume, therefore spalling of FRC was not expected since fiber contents as low as 0.2 to 0.5% by volume are known to increase the percolation of the interfacial transition zones and hence improve vapor pressure dissipation [37]. However, the draft Eurocode [38] now recommends that a minimum of 2 Kg/m^3 of fibers is added to concrete, corresponding to about 2% by volume, to secure protection from elevated temperature. It can be argued that the absence of imposed load, lime expansion and the use of a small fiber content may explain the spalling in some unloaded samples. On the other hand, explosive spalling of HSC is widely reported in the literature (e.g. [39]), but spalling of HSC specimens was not observed in the current study. Ali et al. [40] reported that at low heating rates, like that used in the current investigation, the risk of explosive spalling is minimized. They added that the effect of low permeability on susceptibility to spalling of HSC may be balanced or overcome by the effect of its high splitting tensile strength.

Mass loss due to elevated temperature

The mass loss results are shown in the Figure 10 for model frame specimens and cubes. The cubes had a higher mass loss than the model frame specimens probably due to higher surface / volume ratio of the cubes. In addition, it was observed that reinforcement may hold back the concrete cover, which act as a thermal shield preventing mass loss [1]. Mass loss results are limited in the cited literature. Hoff et. al. [41] heated HSC cylinders (D 150 mm X H 300 mm) made of limestone aggregated having w/c= 0.32 to 700 °C. The recorded mass loss was 6.68%. At higher temperatures a very rapid increase in mass loss was observed due to the dissociation of calcium carbonate in the limestone with the liberation of large amounts of CO_2. Therefore, the results of the current investigation with heating up to 800 °C (12.5% mass loss for HSC cubes) seems in line with the findings of Hoff et. al. [41].

The mass loss of FRC was higher than other types of concrete. This may be attributed to the ease of vapor dissipation in the porous network produced after melting of fibers at 160 °C [28]. In addition, the spalling exhibited by the samples of this type of concrete (see previous section) may have increased the mass loss results. Mass loss of NSC and LMC came in second place after FRC. For NSC, this may be attributed to the higher initial moisture content and permeability of NSC (as suggested by Kalifa et. al., [1]) compared with HSC, and to the spalling observed for NSC samples. The mass loss for LMC was in the same order of magnitude as the NSC. This is may be due to thermal degradation of the polymers in the Latex on heating above 200 °C [42]. The effect of this degradation on the microstructure of the heated LMC needs further study in order to fully understand the observed results for this concrete. The LWAC exhibited the minimum mass loss results. This is probably due to the higher porosity of these samples, which was visible by naked eye after samples preparation. This enabled efficient air drying of LWAC prior to exposure to elevated temperature, hence the moisture content was originally lower than the other samples.

It was found that the loaded specimens exhibited less mass loss than unloaded ones except for FRC specimens. Again the suggestion of Malhotra [4], as explained in the previous section, may apply in this case. In other words, moisture loss was more difficult in loaded samples. In addition, in slabs of loaded samples moisture was mainly lost from the bottom surface of the slabs due to the presence of load bricks. The high mass loss in loaded FRC samples cannot be explained especially if the spalling exhibited by their unloaded counterparts is taken into account.

Sanjayan and Stocks [43] heated NSC and HSC T-beams to 1000 °C after air drying for 3.5 months. They experienced explosive spalling of the HSC beam at 715 °C. The mass loss at 800 °C, 25 minutes from the start of heating, was 1.2 and 6.9%, respectively. The weight loss observed in the unloaded model frame samples was 11.54 and 10.71 %, respectively. The difference between the results of the current investigation and those of Sanjayan and Stocks [43], can be explained by the higher moisture content in the model frame samples, as they were air dried for only 40 days prior to testing. In addition, Sanjayan and Stocks [43] were recording the weights of the T-beams during heating. In the current investigation, the weights were recorded when the samples were cool enough to be handled, i.e. more than 24 hours after the oven was switched off. It was observed that the samples continued to lose weight as they became cooler. This progressive weight loss during cooling was also observed by Kumar and Kumar [19], for beams heated to 1000 °C in 150 minutes and maintained at that temperature for 2.5 hours. It can be argued that this is due to the reformation of calcium hydroxide after cooling, which was originally decomposed into lime and water during heating accompanied by expansion, and surface crumbling or spalling as lime is re-hydrated [2].

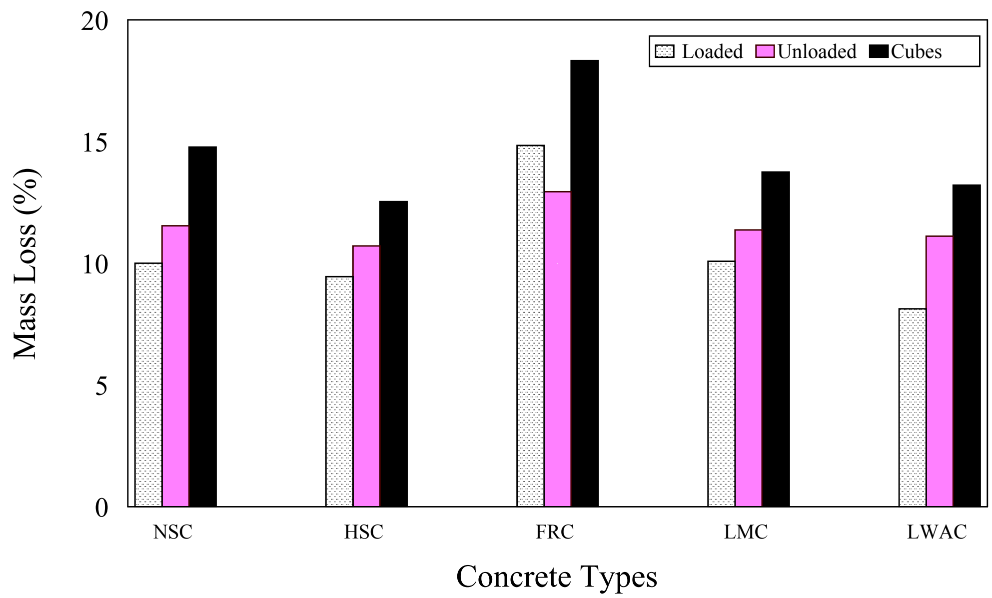

Figure 10 Effect of elevated temperature on mass loss of model frame samples and cubes

Effect of elevated temperature on compressive strength

The compressive strength of the cubes made from the different types of concrete, before and after heating, is shown in Figure 11. Also shown is the percentage loss in compressive strength. It can be seen that the NSC, FRC and LMC had a comparable compressive strength to start with. However, heating to 800 °C, caused a different compressive strength loss for each type of concrete. A high loss was incurred by the LMC, which was even higher than that experienced by HSC. The effect of polymer melting in the latex, upon heating LMC to above 200 °C [42], on its mechanical properties at elevated temperature needs to be fully investigated. On the other hand, the melting of fibers in FRC has lead to quick vapor release and therefore a small strength loss occurred. HSC exhibited a much higher loss in strength than that of NSC, probably because of permeability differences. In addition, Malhotra [4] found that the leaner mixes undergo a smaller proportional reduction in strength when heated compared to richer ones. It would appear that the Leca, used in the preparation of LWAC, disintegrated at the high temperature and hence a very high strength loss was observed.

Chan et. al. [5] heated 100 mm cubes made of natural gravel to 800 °C. Of particular relevance to the current study are their NSC (w/c = 0.57) and HSC (w/c=0.31) samples. They found that the loss in compressive strength was 49 and 70%, respectively. Luo et. al. [44] carried out an identical test on samples made of granite aggregates having w/c = 0.6 and reported a compressive strength loss of 54.7%. Short et. al. [14], while testing similar samples made of limestone aggregates, having w/c = 0.66 and heated to 700 °C, reported a strength loss of 58%. Hoff et. al. [41] prepared plain HSC, high strength FRC and high strength LWAC cylinders, having w/c = 0.32. The HSC and FRC were made of limestone, and fiber content in the FRC was

1.5 kg/m^3. LWAC was made from either expanded slate or expanded slag. After heating to 700 °C, the strength loss was 82, 83, 78 and 75 % for the HSC, FRC, LWAC (slate) and LWAC (slag), respectively. It is clear that the strength loss values are different for the different studies and, in general, are not in agreement with the results of the current investigation. This may be attributed to differences in mix design, types of materials used, sample preparation, moisture conditioning regime prior to heating, sample size and heating rate.

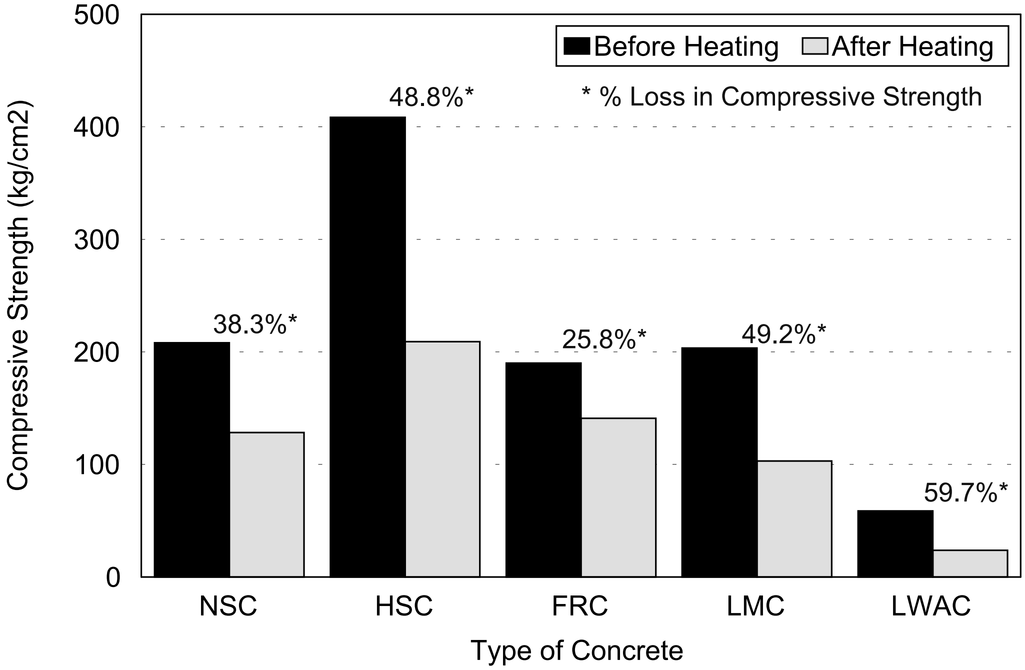

Figure 11 Compressive strength of cubes before and after heating

Effect of elevated temperature on rebound number

In a real fire the strength reduction depends on the temperature to which the concrete was exposed. As concrete is a poor heat conductor, steep thermal gradients are developed across the depth of members. Lin et. al. [45] prepared 200, 300 and 400 mm square columns and heated them in accordance with the BS 476 curve. After 40 minutes from the start of heating the temperature inside the oven reached 800 °C. However, the thermocouples placed at the center of the columns measured only 107.4, 92.9 and 22.4 °C respectively. In a similar test Chan et. al. [17] heated 100 mm thick slabs from one side to 1000 °C within 120 minutes. At this time the temperature at the center of the slab was only 380 °C. Chan et. al. [17] estimated the compressive strength across the depth of the slab at distances of 10, 30, 50 and 70 mm from the surface exposed to heat using Schmidt hammer. They reported that the strength was 12, 22, 23 and 48 MPa, respectively. Their procedure is very difficult to apply during insitu assessments of compressive strength after fire accidents as a sound, debris free surface has to be exposed and prepared for carrying out the test at each depth.

The difference between the surface and center of test samples subject to heat was found to be dependant on the heating rate and member dimensions. Slower heating rates and thinner sections result in temperature uniformity at a certain time during the heating cycle. Nassif et. al. [46]

heated concrete cores of diameter 75 mm having w/c=0.4 and made of limestone aggregates. They found that at 287 °C, which was reached 100 minutes from the start of heating, the thermocouples placed on the surface and at the center of the cores recorded the same temperature. In the current study, the heating rate was also slow (see Figure 7), the heating cycle lasted for four hours, and the members in the model frame samples were slender (40 mm thick slab and 100 mm square columns and ground beams). Therefore, the temperature uniformity is expected to occur. Hence, rebound number measurements may be representative of the hardness for the whole sample.

The results for the rebound number of the model frame samples are shown in Table 3. The recorded rebound numbers before the test were different for various members in the model frame samples, the slab exhibiting lower values than the columns and ground beams, probably due to the difference in thickness as thin members may vibrate on hammer impact [29]. It is clear that the heating has greatly reduced the rebound number results. The columns and ground beams lost an average of 61 and 51% of their rebound number, respectively, regardless of the loading state, whereas the slabs lost an average of 77% in the loaded state and 95% in the unloaded state. The loss in rebound number was smaller in the loaded slabs as the readings were taken on the upper surface of the slab, which was insulated by the load bricks. However, it appears that the hammer was not able to detect the difference in damage to the columns and ground beams between the loaded and unloaded states.

Short et. al. [14] carried out Schmidt hammer tests on 100 mm cubes, made with limestone aggregates and having w/c between 0.62 and 0.66, which were heated to 700 °C. They found that the residual rebound number was 35% of its original value prior to heating. The values obtained in the current investigation seem, therefore, reasonable.

The between member coefficient of variation, for the model frame samples before heating, was 8-15%. This is in line with the findings of Bartlett and MacGregor [47] who estimated that the compressive strength coefficient of variation for several members cast from different batches was 13%. The corresponding value after heating, for the model frame samples in the current investigation, was 21 - 92%. Therefore, exposure to heat has increased the rebound number differences, and hence the strength variation, between members of the same sample.

It can be seen from Table 3 that in some cases, the rebound number was too low to be recorded by the hammer. Some of recorded readings after heating are of questionable validity since Bungey and Millard [29] stated that Schmidt hammer is most suitable for estimating concrete strengths in the range of 200-600 kg/cm^2, corresponding to rebound numbers between 20 and 60 approximately. They added that if the strength of the concrete is between 50 and 250 kg/cm^2, then it is recommended that a pendulum type rebound hammer is used. To the author's knowledge, this device is not readily available for many insitu investigations.

It can be argued that the conventional method for applying the Schmidt hammer test for assessment of insitu concrete strength should not be used for strength assessment of concrete that has been subjected to fire for the following reasons:

a) The strength is expected to vary across the depth of each structural member, surface readings would not be representative of the concrete strength. Exposing inner parts of the member is difficult to perform for all members to be examined.
b) Different members within a structure are affected by fire to different degrees, depending on their thickness, restraint, temperature reached during fire and loading state. Therefore, the damage suffered by members is more complex than that detected by the hammer.
c) The reduction in rebound number is sometimes too high. Readings may not be recorded or may be invalid. This renders the conventional Schmidt hammer unsuitable for measurements.

Table 3 Rebound number results for members in different types of model frame samples before and after heating

Frame Type and Loading State	Columns		Ground Beams		Slab	
	Before Heating	After Heating	Before Heating	After Heating	Before Heating	After Heating
NSC Loaded	30	12	31	17	24	12
NSC Unloaded	32	14	32	22	25	N/A
HSC Loaded	40	24	39	28	31	18
HSC Unloaded	40	23	42	26	32	9
FRC Loaded	32	17	32	19	25	N/A
FRC Unloaded	31	15	30	17	25	N/A
LMC Loaded	28	12	28	16	24	N/A
LMC Unloaded	30	15	33	19	24	N/A
LWAC Loaded	11	N/A	13	N/A	11	N/A
LWAC Unloaded	13	N/A	14	N/A	10	N/A

Effect of elevated temperature on ultrasonic pulse velocity

The percentage loss in ultrasonic pulse velocity (UPV) for the different members in the model frame samples is shown in Figure 12. The deterioration of the LWAC was excessive, and therefore no readings could be recorded for frames made with this type of concrete. For the other four types of concrete the UPV loss exhibited by the various members ranged from 53.6 to 89.8%. These values were for the FRC ground beams in the unloaded and loaded states, respectively. It can be seen that the loss of UPV, for members in model frames, depended not only on the compressive strength of the original concrete, but also on the type of concrete, type of member and stress state of the frame.

Slabs of the unloaded LMC and HSC exhibited the highest UPV losses in their frames as these members showed more cracking when visually examined compared to the columns and beams. Although spalling was observed in unloaded NSC columns, the ground beam seem to have suffered the largest UPV loss in NSC. The ground beams in HSC, FRC and LMC frames did not suffer as severely. Structural analysis indicated that the ground beams were under a tensile stress in the frames [48]. Chan et. al. [5] reported that the splitting tensile strength of concrete was reduced more sharply, compared to compressive strength, after exposure to elevated temperature. They added that the rate of loss in tensile strength was slightly lower in HSC compared to NSC. Chen and Liu [49] found that HSC heated to 800 °C retained 10% of its original splitting tensile strength, but with adding as little as 0.6% of polypropylene fibers, the retained splitting tensile strength became 30% of its original value. Therefore, the deterioration of the NSC ground beams can be attributed to the fact that NSC had originally a low tensile strength, whereas with HSC and FRC mixes the original tensile strength [50], and also the rate of tensile strength loss, were somewhat improved. It is not clear why the LMC ground beams showed improved performance in spite of melting of the polymers in the latex above 200 °C [42]. This observation needs verification by more tests including microstructure examination by SEM. Spalling was observed in FRC columns. However, it would appear that the melting of the fibers has caused a greater UPV loss in the slab compared to the ground beams in FRC, probably because of the member thickness difference.

The columns in loaded HSC model frames, which were made from concrete having a cube compressive strength of 40.8 MPa; i.e. cylinder compressive strength of 32.8 MPa, lost 64% of their UPV due to temperature exposure. Lie et. al. [15] heated two loaded reinforced concrete columns, 305 mm square cross section and 3810 mm high, made of siliceous aggregates for either one or two hours to 800 °C. Companion cylinders were tested on the day of heat application and gave a compressive strength of 40 MPa. The average UPV readings before heating for the columns were 4510 and 4560 m/s. After heating, the readings for the column heated for 1 hour ranged between 1200 to 2000 m/s and those for the column heated for 2 hours were between 1000 to 1600 m/s. It can be seen that the columns lost between 55.6 to 73.4% or 64.9 to 78.1% of their UPV values when heated for 1 and 2 hours, respectively. Therefore, the results of the current investigation are comparable to those of Lie et. al. [15].

The ground beams in the NSC, HSC and FRC exhibited higher UPV loss compared to other members in the same loaded model frame. The ground beams were under approximately 40% higher tensile stress in the loaded frames compared to their unloaded counterparts [48]. It would appear that these tensile stresses magnified the internal cracking from elevated temperature, hence a significant loss in UPV was observed in the ground beams of loaded frames. The ground beams in loaded LMC did not exhibit a similar behavior, in fact the LMC ground beams showed the least reduction in UPV amongst all members in the loaded frames. At ambient temperatures it was found that the latex increases the tensile strength of concrete and bond with steel reinforcement [51]. Moreover, Fu and Chung [52] found that LMC has a lower coefficient of thermal conductivity compared to the control concrete without the latex. However, Omaha et. al. [42] found that the maximum temperature limit for retaining the useful strength properties in LMC is 150 °C. Therefore, the results of the current investigation cannot be explained in light of the current knowledge on the behavior of LMC at elevated temperatures. Visual observation, as discussed above, revealed deflection in the NSC and FRC and cracking in the HSC and LMC slabs. This has been reflected in the UPV loss for the slabs in the loaded samples.

In comparing the UPV loss between loaded and unloaded frames, it can be seen that there was no significant difference between the UPV loss for the columns in the loaded and unloaded states (one sided, paired Student t-Test returned a probability of only 0.37). This is probably because the applied load was much smaller than the ultimate capacity for the columns. It is interesting to note that the slab of loaded FRC frame exhibited a much higher loss in UPV compared to the unloaded counterpart. Although micro-structural damage from fiber melting is expected to be the same for both slabs, the loaded FRC also exhibited significant deflection i.e. macro-cracking which probably had a profound effect on UPV loss for the loaded slab. On the other hand, UPV losses for loaded slabs of the other types of concrete were either slightly (NSC and HSC) or significantly (LMC) lower than those for the unloaded ones. This was explained by Bailey [28], who reported that restrained loaded slabs, are under a compressive membrane action provided that their deflection does not exceed half their depth. It is postulated that this compressive membrane action has contributed to the reduced internal cracking, as detected by the UPV measurements, in the loaded slabs compared to their unloaded counterparts.

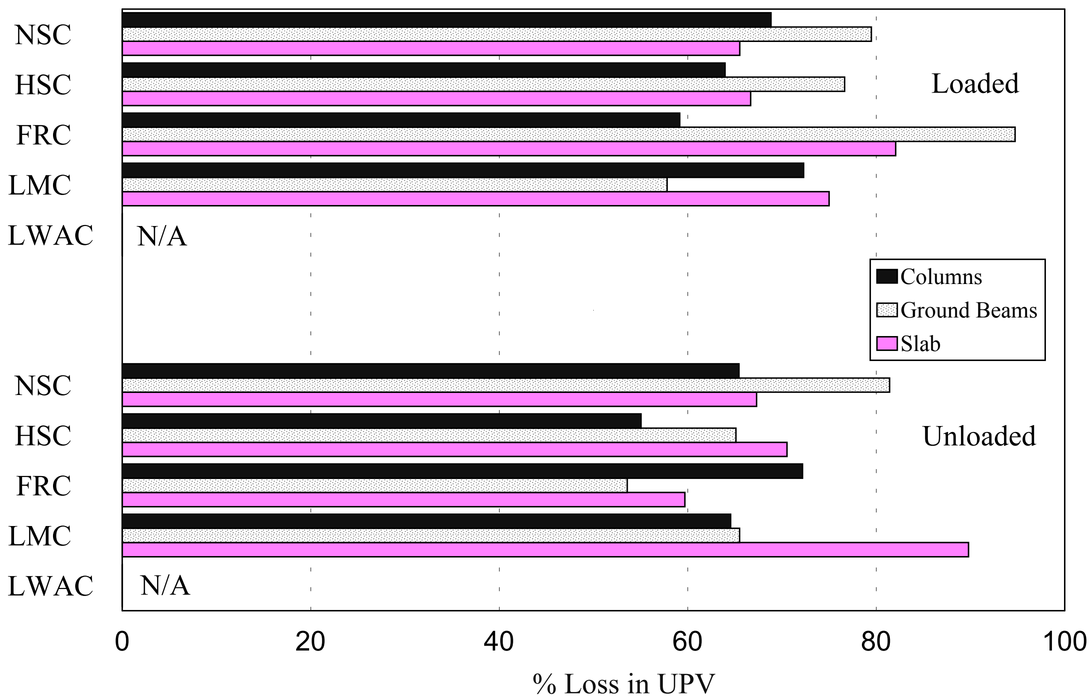

Figure 12 Percentage loss in ultrasonic pulse velocity for members in the model frames

The average UPV loss for each frame sample is compared to the loss of UPV experienced by the cubes made from the same types of concrete in Figure 13. The UPV loss for the cubes was greater than the average values for the model frame samples, and ranged between 69.5% for HSC and 94.23% for LWAC. It would appear that the % loss in UPV, for small laboratory samples, is dependant on the w/c and/or compressive strength of the original concrete. A similar observation was made by Malhotra et. al. [53] who found that concrete cylinders, made from natural gravel and having w/c ratio of either 0.23 or 0.71, heated to 450 °C for 72 hours, lost 44.2 and 58.4 % of their UPV values. Short et. al. [14] found that 100 mm cubes, having w/c = 0.62 to 0.66 and made of limestone aggregate lost 90% of their UPV values when heated to 700 °C for 1 hour.

Effect of elevated temperature on the UPV-compressive strength relationship

Many investigators studied the pulse velocity-compressive strength relationship. Kaplan [54] presented **linear** relationships between the two parameters and reported that the relationship depended on the aggregate/cement ratio of the concrete. In addition, he found that if the measurements are carried out on cubes (standard compressive strength), the relation is not the same as that produced by carrying out the tests on columns (core compressive strength). Chung and Law [32] proposed an **exponential** relationship between the UPV for cement paste and the concrete compressive strength. They calculated the UPV of the paste from an empirical equation that takes into account the aggregate cement ratio, the UPV for the aggregates used in concrete and the measured UPV of the concrete. Nasser and Lai [12] tested concrete cylinders, concrete blocks and reinforced slabs. They fitted **power** relationships between the measured UPV and compressive strength and reported that the coefficient of correlation for relationship including the results from the slab was worse than that for the small non-reinforced samples.

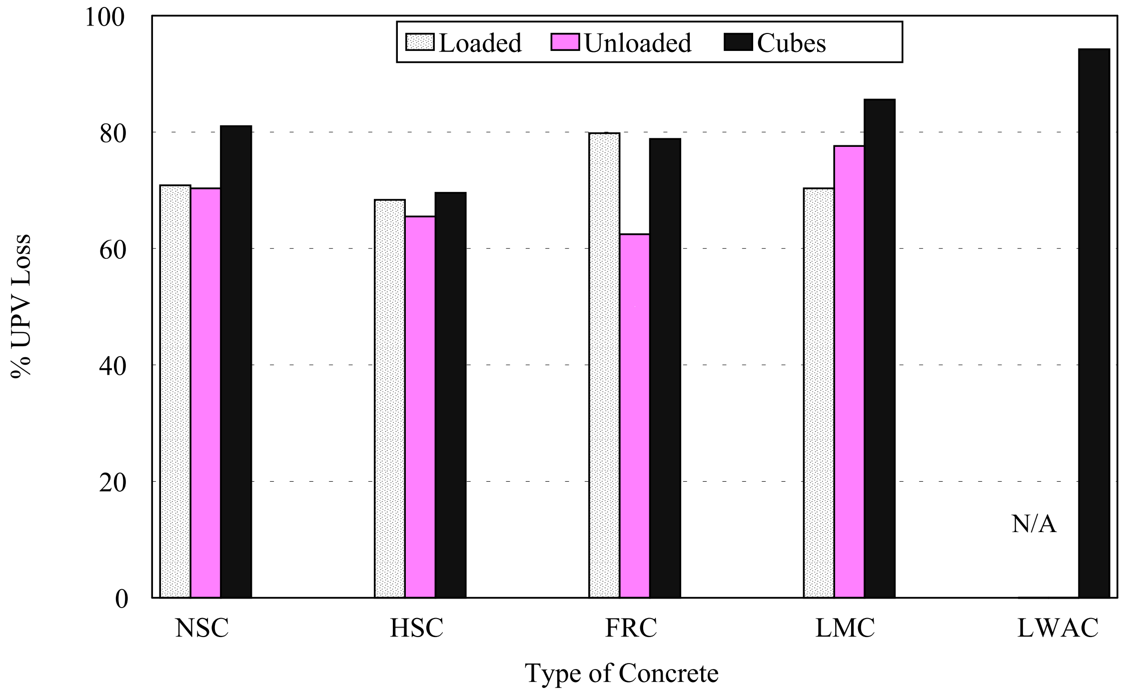

Figure 13 Percentage loss in ultrasonic pulse velocity for the model frames and cubes

UPV measurements were carried out on six cubes from each mix in this investigation. Before the measurements, three cubes were heated to 800 °C whereas the others were kept at room temperature. Subsequently, all cubes were tested for compressive strength. The UPV – compressive strength relationship for the heated and unheated cubes is shown in Figure 14. It should be stressed that these relations are only valid for the concrete tested. It can be seen that heating had a profound effect on the relationship. For example, based on the these curves, a UPV reading of 3 km/sec means that the compressive strength of the concrete is 82 kg/cm^2 , if the concrete was not subject to elevated temperature. The same reading would indicate that the compressive strength was 382 kg/cm^2 where the concrete has been affected by elevated temperature. This is in agreement with Lie et. al. [15] who pointed out that there is a significant decrease in measured pulse velocities for a given compressive strength for fire damaged concrete compared to the undamaged counterpart. Further investigation is needed in order to incorporate this effect into the recommended procedures for the assessment of structures after fire. In addition, more work is needed to establish the effect of thermal gradients in full scale structural members on both the core compressive strength and measured pulse velocity after a fire.

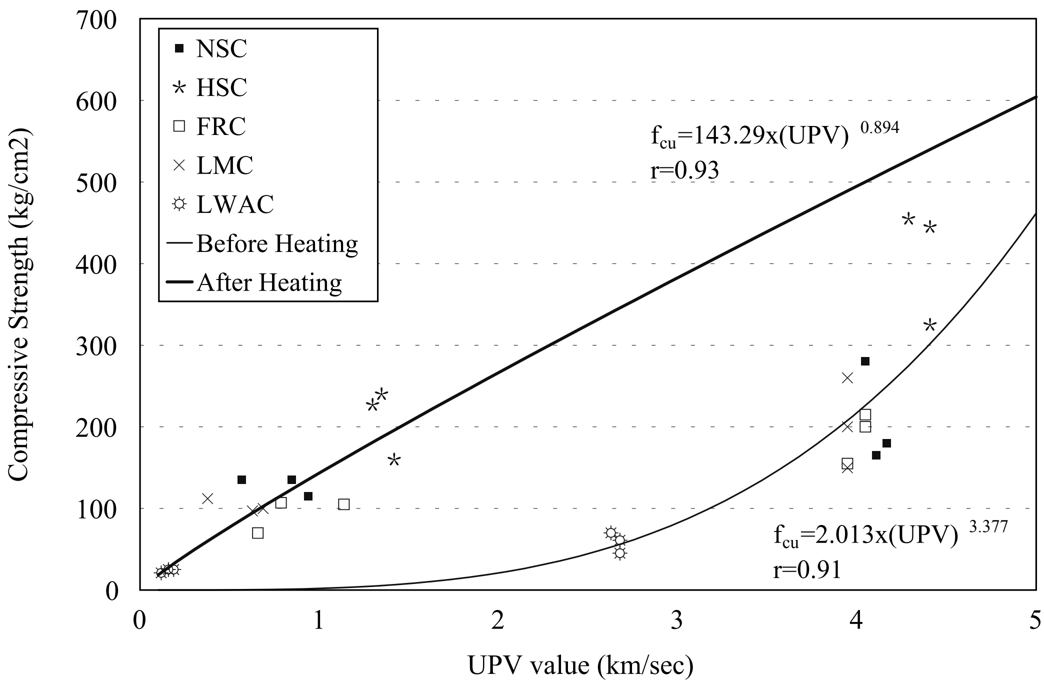

Figure 14 Effect of elevated temperature on the UPV- compressive strength relationship

CONCLUSIONS

1- A lot of research into the effect of elevated temperatures on concrete has been conducted, but the behavior of real structures in real fires is an area which needs a lot of work. Unfortunately, full scale tests are costly, therefore a valid option would be to test scaled down models like those built in the current investigation.

2- Many lessons can be learned from tests on models. In this investigation it was found that the deterioration suffered by a member depends not only on the type of concrete, from which the model frame was made of, but also on the type of member and stress state.

3- The Schmidt hammer test is not suitable for assessing concrete after a fire, for three reasons. Firstly, in a real fire the damage to the surface of the concrete is usually more severe compared to the interior of the members, the readings would not represent the quality of concrete. Secondly, the internal damage to members in fire, depends on the stress state and restraint, and therefore is more complex than just the loss in surface hardness as detected by the hammer. Finally, fire reduces the rebound number greatly and this in turn makes readings obtained using the conventional hammer invalid.

4- Pulse velocity measurements reflected the internal damage suffered by members, but the results need to be interpreted in light of materials properties, restraint, visual examination and stress states of members within structures. To illustrate this, most ground beams in loaded frames of the current investigation, exhibited a large loss in ultrasonic pulse velocity after heating, probably because they were in tension and the tensile strength is sharply reduced by elevated temperature. On the other hand, the deflected slabs in the loaded frames, did not show a high loss in pulse velocity, probably because they were under a compressive membrane action.

5- Pulse velocity-compressive strength relationship was profoundly affected by fire. For example, a UPV reading of 3 km/sec would indicate a compressive strength of either 382 or 82 kg/cm^2, depending on whether the concrete has been or has not been subject to elevated temperature, respectively. This needs to be taken into account in recommended procedures for assessing structures after fire.
6- More work is needed to establish the effect of thermal gradients in full scale structural members on both the core compressive strength and measured pulse velocity after fire.

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