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Analysis of temperature degraded concrete at high temperature by applying of non-linear characteristics

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Abstract. Concrete structures are commonly exposed to thermal loads as a result of the structure, ambient conditions, the heat of hydration, or exposure to fire. Therefore, there has been a growing interest in the research of advanced monitoring and analysis of concrete structures subjected to thermal load. Non-linear characteristics have been used to identify thermal damage evolution in concrete structures. The present paper investigates the effects of a high temperature on selected physical properties of concrete. Concrete properties were monitored and analyzed in several thermal steps up to 1200°C. Concrete specimens were heated in a programmable laboratory furnace at a heating rate of 5°C/min and loaded at six temperatures, 200°C, 400°C, 600°C, 800°C, 1000°C, and 1200°C, with each maintained for 60 minutes.

1. Introduction
Interest in the behaviour of concrete under high temperatures has recently been fuelled by fires of industrial, government- or private-owned buildings, tunnels, and other building structures. An interesting principle of non-destructive testing of heat-degraded concrete at high temperatures is presented [1]. The method used involves measuring the wave propagation through material structures and its effect on higher harmonics. Therefore, the frequency spectrum of each structure was computed using fast Fourier transform. Structural Health Monitoring aims to improve the knowledge of the safety and maintainability of civil structures and infrastructures [2, 3].

There are changes expected if concrete is heated up to [4]:

| Temperature (°C) | Changes |
|------------------|---------|
| 200°C            | slow capillary water loss and reduction in cohesive forces as water expands, ettringite dehydration, C-S-H gel dehydration, gypsum decomposition (CaSO₄ 2H₂O), physically bound water loss, |
| 400°C            | break up of some siliceous aggregates (flint), |
| 600°C            | portlandite decomposition Ca(OH)₂→CaO+H₂O, quartz phase change β→α in aggregates and sands, |
| 800°C            | second phase of the C-S-H decomposition, formation of β-C₂S, |
| 1000°C           | dolomite decomposition, calcite decomposition CaCO₃→CaO+CO₂, carbon dioxide release, ceramic binding initiation which replaces hydraulic bonds, |
| 1200°C           | basalt melting, |
| over 1200°C      | total decomposition of concrete, melting. |

Poor material homogeneity and, in some cases, shape complexity of some units used in the building industry, are heavily restricting the applicability of “classical” ultrasonic methods [5, 6]. The dynamic material response of samples with damaged material integrity was demonstrated by the formation of...
different harmonics in the response frequency spectra [7]. The pulse echo method monitors changes in the material structure based on a change in the response to a pulse generated. Using a mechanical impact to induce microstrain is advantageous for concrete testing because it allows for testing of larger concrete specimens offering potential field transportability [8].

2. Experimental set-up
This part describes the experiment and the evaluation of the generated ultrasound signals when testing their passage through the material of concrete specimens after a heat load.

The tests were performed on beams with a cross section of 100 mm by 100 mm and length of 400 mm as shown in Figure 1. Three types of beams were made according to Table 1 with the kind of the coarse aggregate having been thus changed. Starting at a normal temperature of 22°C, the specimens were heated at a heating rate of 5°C/min up to a pre-set temperature maintained for 60 minutes and then placed in a room with a normal temperature of 22°C.

| Table 1. Mixture monitored. |
|-----------------------------|
| A (kg/m$^3$) | B (kg/m$^3$) | C (kg/m$^3$) |
|----------------|-------------|-------------|
| cement CEM I 42.5R | 345 | 345 | 345 |
| sand 0/4 | 813 | 813 | 813 |
| coarse aggregate 4/8 | 1010 | | |
| coarse aggregate 8/16 | 1010 | | |
| coarse aggregate 11/22 | | 1010 |
| water | 176 | 176 | 176 |
| super plasticizer | 3 | 3 | 3 |

The pre-set temperatures were 200°C, 400°C, 600°C, 800°C, 1000°C, and 1200°C. The beams were tested at a normal temperature.

![Figure 1. Experimental set up.](image)

The specimens were excited by a sensor placed in the centre of a square side. Impulses were generated by the ultrasound equipment PUNDIT. The acoustic emission system XEDO was applied to detect the waves. Three piezoelectric sensors were placed on different sides of the specimen. The first sensor was situated near the exciter on the perpendicular side, the second one on the opposite side of the specimen being 50 mm away from the opposite side on the side perpendicular to the first one and the third sensor was on the same side as the first one but 50 mm away from the opposite edge.
Twenty specimens, made after thermal degradation by each temperature, were monitored by these tests. The errors of the measured and computed values do not exceed five percentage points.

3. Results
The results are presented as an analysis of the first eigenfrequency computed from the frequency spectra of the specimen response characteristic as shown in the following tables and figures.

Table 2. Cube compression strengths of three different mixtures.

| Temperature (°C) | A (MPa) | B (MPa) | C (MPa) |
|-----------------|---------|---------|---------|
| 20              | 65      | 75      | 50      |
| 200             | 63      | 63      | 43      |
| 400             | 54      | 57      | 48      |
| 600             | 46      | 41      | 28      |
| 800             | 31      | 31      | 24      |
| 1000            | 14      | 8       | 6       |
| 1200            | 16      | 10      | 28      |

![Figure 2](image-url)

**Figure 2.** The cube compression strength ($f_c$) on the degraded temperature (T).

From the values of the compression strength on cubes (see Table 2 and Figure 2), it can be concluded that, for all temperatures, mixture B shows the biggest loss of strength relative to a reference temperature. Interesting is the behaviour of mixture C where there is a decrease as expected if heated to 200°C, however, with an increase if heated to 400°C, which could be accounted for by the fractions of the aggregate used being near. Then, an increase in the relative compression strength should also be pointed out at a temperature of 1200°C; for particular mixtures, this increase is caused by a new crystalline form, Wollastonite, being built at a temperature of about 1100°C. This increase is the greatest in mixture C and, again, this could be accounted for by the vicinity of the fractions of the aggregate used.
For analysing the behaviour of the samples by the pulse-echo method, the first harmonic frequencies were calculated of the signal monitored using fast Fourier transform. The values of the eigenfrequencies found for each sample at various degrees of degradation are shown in Table 3. The changes of these values relative to the basic value of the sample set at a temperature of 20°C can be seen in Figure 3.

Table 3. Frequencies of three different mixtures.

| Temperature (°C) | A (kHz) | B (kHz) | C (kHz) |
|------------------|---------|---------|---------|
| 20               | 43.9    | 90.3    | 45.4    |
| 200              | 45.4    | 93.2    | 44.4    |
| 400              | 41.9    | 85.0    | 42.8    |
| 600              | 17.6    | 28.3    | 16.1    |
| 800              | 16.6    | 22.9    | 14.2    |
| 1000             | 7.3     | 14.6    | 14.6    |
| 1200             | 14.6    | 24.7    | 25.4    |

Figure 3. The relative eigenfrequency (f) on the degraded temperature (T).

The frequency value increasing after temperature increase to 200°C probably causes an improvement of the structure bonds. This occurred in mixtures A and where there is more space between the aggregate particles for self-repair of the cement due to the ambient humidity during the test. In mixture C with more finer aggregate particles, no such effect has been observed. As the temperature increases further, a decrease is apparent in the frequency values for all mixtures. Only for the last temperature of 1200°C, again, a reaction can be observed to the appearance of Wollastonite of the mixture, which is again most marked in mixture C.

A similar sample behaviour pattern can also be observed if the decrease of the higher harmonics is linearized for particular samples. Here, the expected exponential decrease of the harmonic component
amplitudes is linearized by the spectrum being transformed into decibels. The values can be found in Table 4 with their relationships to the basic-temperature sample in Figure 4.

Table 4. Slopes of three different mixtures.

| Temperature (°C) | A (dB/kHz) | B (dB/kHz) | C (dB/kHz) |
|------------------|------------|------------|------------|
| 20               | -0.494     | -0.414     | -0.487     |
| 200              | -0.586     | -0.583     | -0.415     |
| 400              | -0.661     | -0.448     | -0.390     |
| 600              | -1.122     | -0.644     | -0.568     |
| 800              | -1.728     | -0.471     | -0.774     |
| 1000             | -2.383     | -1.842     | -1.647     |
| 1200             | -1.391     | -1.390     | -0.763     |

Note that Table 4 shows the values of the attenuation \( k \) for the equation

\[
S_n = c \cdot \exp(k \cdot f_n)
\]  

where \( S_n \) is the amplitude of the frequency spectrum, \( f_n \) is the frequency, \( n \) is the number of the harmonic and \( c \) and \( k \) are constants. It is clear that \( f_n = n \cdot f_1 \) where \( f_1 \) is the first harmonic [9]. A change in the first harmonic along with the slope of the attenuation of the harmonics account for the changes in the observed samples.

![Figure 4. The relative slope of linear approximation (k) on the degraded temperature (T).](image)

4. Conclusion

The pulse-echo method seems to be well-suited for determining the degree of damage to the heat-degraded concretes. As shown, the results of a non-destructive pulse-echo method can be well correlated with the destructive pressure test. This comparison is mainly evident in Figures 4 (the non-
destructive testing of the pulse-echo method) and 3 (the destructive pressure test) when the characters are similar.

In the near future, we expect the methodology of these techniques to be developed and applied to various materials testing procedures. This method may also help create or improve a numeric model of wave propagation in concretes of different structures. From the evaluation of these samples, it can be assumed that, with the increasing size of the coarse aggregates, the thermal resistance of the concrete mixture decreases.

It has been shown that analyzing high-frequency dynamic characteristics generated by a pulse signal may indirectly influence the nature of an observed structure. The changes in the compression strength of heat-degraded samples are correlated with the changes in the dynamic properties of a structure.

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References
[1] Felicetti R, Monte F Lo and Pimienta 2017 A new test method to study the influence of pore pressure on fracture behaviour of concrete during heating Cement and Concrete Research 94 pp 13–23
[2] Ditommaso R and Ponzo FC 2015 Automatic evaluation of the fundamental frequency variations and related damping factor of reinforced concrete framed structures using the Short Time Impulse Response Function (STIRF) Engineering Structures 82 pp 104–112
[3] Rashidyan S, Ng TT and Maji A 2017 Estimating the Depth of Concrete Pier Wall Bridge Foundations Using Nondestructive Sonic Echo Journal of Nondestructive Evaluation 36(3) art. No~56
[4] Piasta J 1989 Heat deformations of cement paste phases and the microstructure of cement past Materials and Structures 17(6) pp 415–420
[5] Neild SA, Williams MS and McFadden PD 2003 Nonlinear vibration characteristics of damaged concrete beams Journal of Structural Engineering-Asce 129(2) pp 260–268
[6] Miyamoto A, King Mw and Fujii M 1991 Analysis of Failure Modes for Reinforced-Concrete Slabs under Impulsive Loads ACI Structural Journal 88(5) pp 538–545
[7] Korenska M and Manychova M 2010 New possibilities of non-destructive testing of ceramic specimen integrity Ceramics-Silikaty 54(1) pp 72–77
[8] Jin J, Moreno MG, Riviere J and Shokouhi P 2017 Impact-Based Nonlinear Acoustic Testing for Characterizing Distributed Damage in Concrete Journal of Nondestructive Evaluation 36(3) arc. No~51
[9] Pazdera L, Smutny J and Topolar L 2011 Applying High Order Statistics Analysis at Non Destructive Evaluation of Concrete Tiles Experimentalni Analyza Napeti - Experimental Stress Analysis (14 EAN) pp 309–314