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Determination of condition of concrete samples of different mixture degraded by high temperatures by acoustic non-destructive method Impact-echo

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Abstract

The advantage of concrete over other building materials is its fire-resistive properties. The civil structures must be able to withstand dead and live loads without collapse even though the rise in temperature causes a decrease in the strength and modulus of elasticity for concrete. At current state determination of damage in concrete is performed mainly by microscopic analysis which is a destructive method. It requires a significant time interval to produce results and by simple compressive strength tests which also requires sample removal. On the other hand, the inspection by Acoustic Non-Destructive Testing methods [1], [2], [3]. (Impact-echo, ultrasound measurement etc.) can be applied, when macro-cracking or another form of damage appears.

Impact echo method is one of the oldest acoustic testing method in civil engineering [4]. We excite the test specimen by mechanical impulse and then listen to response [5]. Skillful observer then can assess the condition of construction. Right interpretation of measured data is crucial part for this acoustic non-destructive method. In this paper, the possible usage of impact echo method used for evaluation of condition of high temperature degraded concrete structures [6] is examined. It is focused on two mixtures different by coarse aggregate 8/16 and 11/22 mm. The temperature load is divided to 200, 400, 600, 800, 1000 and 1200 °C sets. The signals were excited by mechanical hammer, and response in form of mechanical wave was recorded by piezoelectric sensor. The signal was then converted to frequency spectrum by Fast Fourier Transform [7].

We assessed two testing positions of exciter and receiver, thus two frequency spectrums for each temperature set. A comparison of longitudinal and transverse wave is presented and as a guideline for material properties destructive tests have been made. A correlation between condition of temperature degraded concrete samples obtained by destructive tests with dominant frequency peaks obtained by non-destructive method is discussed and evaluated.

Introduction

Impact echo method was invented at the U.S: National Bureau of Standards in 1980 and developed at Cornell University, in Ithaca, New York. Professor Mary J. Sansalone was principal inventor of the impact-echo method and a leading authority on the use of transient stress waves for non-destructive evaluation of heterogenous materials [8].

Impact-echo method belongs to stress wave propagation non-destructive methods based on the use of transient stress waves. A transient stress pulse is introduced into a structure by mechanical impact at a point on the surface. This pulse travels into the structure as dilatational (P) and distortional (S) waves and along the surface as a Rayleigh (R) wave (Figure 2.). The P- and S-waves propagate into the structure along spherical wavefronts and are reflected by internal cracks, voids, interface between different mediums and by external boundaries of the structure [9]. A P-wave is associated with normal stress, while an S-wave is associated with shear stiffness. A Rayleigh wave, also called a surface wave or R-wave, propagates along the surface of a solid, and particle motion is retrograde elliptical [5].

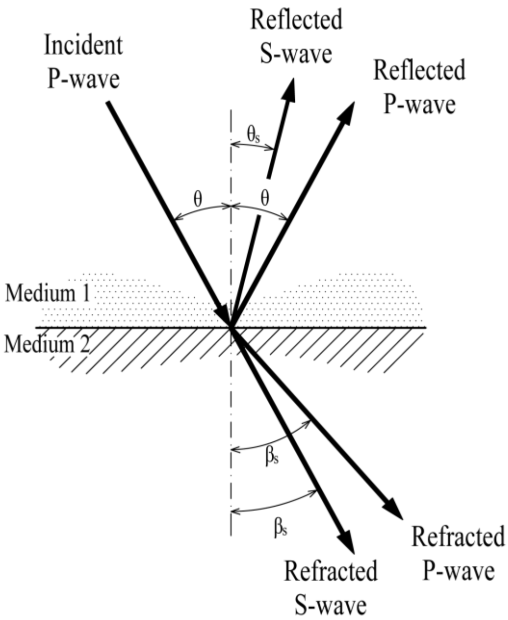

Figure 1. Reflection and refraction of P-wave [5].

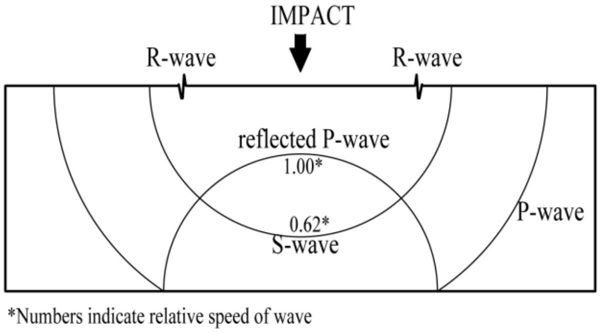

Figure 2. Different types of waves [4].

When a P- or S-wave front is incident on a boundary between dissimilar media, “specular” reflection occurs (Figure 1.). At a boundary between two different media only portion of a stress wave is reflected. The remainder penetrates into the underlying medium (wave refraction). The angle of refraction, β, is a function of the angle of incidence, θ, and the ratio of wave speed, C_2/C_1, in the different media, and is given by Snell’s Law. Depending on the angle of incidence, a P-wave can be partially reflected as both P- and S-waves and can be refracted as both P- and S- waves.

The portion of an incident ray of a P-wave that is reflected at an interface between two media depends on the specific acoustic impedances of each medium (equation 1.1). Typical values of acoustic impedances are shown at Table 1. [5].

$$Z = \rho \cdot C_p \tag{1}$$

Table 1. Specific acoustic Impedances [5].

Material	Density [kg/m^3]	P-wave Speed [m/s]	Specific Acoustic Impedance [kg/m^2·s]
Air	1.205	343	0.413
Concrete*	2300	3000-4500	6.9-104 x 10^6
Granite	2750	5500-6100	15.1-16.8 x 10^6
Steel	7850	5940	46.6 x 10^6

**Concrete density depends on its mixture.*

Material properties

Concrete is heterogenous composite made by cement as a binder, fine aggregate and coarse aggregate as filler and additives. In most static bearable structures concrete is also densely reinforced with steel bars. When mechanical P-wave travel through the concrete specimen, on every disparity such as cracks, air voids, defects, external boundaries or interface between concrete and reinforcement, it reflects and refracts and behave as a new source of P- and S-waves.

Table 2. Review of changes in microstructure that occurs during temperature load [10].

Temperature	Changes
20 – 200 °C	Loss of physically bounded water and steam expansion, thus loss in binding force in concrete. Beginning of dehydration of CSH gel. - 80 °C – 150 °C dehydration of ettringite. - 150 °C – 170 °C decomposition of gypsum $CaSO_4 \cdot 2H_2O$.
300 – 400 °C	Cracking of silicate aggregate (350 °C). Critical temperature for water (374 °C) – after this temperature, there can be no physically bounded free water.
400 – 500 °C	Decomposition of portlandite $Ca(OH)_2 \rightarrow CaO + H_2O$.
500 – 600 °C	Quartz change from β phase to α phase at 573 °C.
600 – 800 °C	Second decomposition phase of CSH gel's and production of β-C_2S.
800 – 1000 °C	Beginning of ceramic bond, which substitutes hydraulic bonds accompanied by production of CO_2. - Decomposition of dolomitic limestone at 840 °C. - Decomposition of calcite $CaCO_3 \rightarrow CaO + CO_2$ at 930 °C – 960 °C.
1000 – 1200 °C	Production of Wollastonite β ($CaO \cdot SiO_2$). - Melting of basalt starts at 1050 °C.
≥ 1300 °C	Total degradation of concrete, loss of mechanical properties. Some compounds start to melt and partial sintering occurs.

Intact healthy well compacted concrete elements have very few defects, and the measured signal is clear from noise and easily readable. Vice versa damaged concrete elements have cracks, bigger air voids, and larger amount of disparities. In high temperature degradation, material changes occur, and material properties such as density, compressive strength and flexural bending strength are changing.

During temperature load many changes occur in concrete, as seen in Table 2. First critical section of temperature load is between 400 °C and 600 °C, where physical free and bounded water and chemical bounded water vaporize and gives rise to pressure in pores and cracks, incapable of leaving the concrete. This leads to spalling for low performance concrete and explosive spalling for high performance concrete [11], [2].

The second critical section is around 1000 °C, where concrete reaches the bottom of its mechanical properties and ceramic bounds do not appear yet. Concrete degraded by this temperature is fragile, aggregate and cement matrix almost lost its binding force.

After 1100 °C partial sintering and ceramic bonds occurs, which leads to sintered structure and thus slight improvement in mechanical properties.

Mixture and degradation

For test specimens, two different mixtures were designed with the usage of different coarse aggregate (Table 3). Coarse aggregate was chosen in order to test concrete of different quality, and observe changes in measured dominant frequencies and destructive tests.

Table 3. Mixture designs.

Compounds	Weight for 1 m^3 [kg]	
	Mixture A	Mixture B
Portland cement CEM I 42.5 R Mokrá	345	
Fine aggregate 0/4 mm (Žabčice)	813	
Coarse aggregate 8/16 mm (Olbramovice)	980	–
Coarse aggregate 11/22 mm (Olbramovice)	–	980
Super-plastizer additive SicaViscocrete 2030 (0,8 % mc)	3.1	
Water (w/c = 0,5)	176	

In this experiment beams of dimension 0.1 x 0.1 x 0.4 m were used as test specimens. Test specimens were created in steel form and after demolding, they were stored in water for 28 days. After that, they were stored at laboratory conditions of 21 °C and relative humidity 60 – 80 % for 7 days. Test specimens were dried in laboratory dryer for 72 hours at 110 °C. By this we removed most of the physically bounded water, which could otherwise lead to explosive spalling and potentially damaging the furnace.

Each mixture was then divided into one intact reference set (kept at 20 °C) and temperature sets which were degraded at 200 °C, 400 °C, 600 °C, 800 °C, 1000 °C and 1200 °C. After drying, the test specimens were burn in ceramic furnace Rhode KE 130B at the heating rate of 5 °C/min. Selected temperatures were maintained for 60 minutes. Test beams were then spontaneously cooled in furnace to laboratory temperature.

Measuring process

Studies have shown, that impact-echo method can be very reliable and effective tool for evaluating fire damaged concrete structures [12], [6], [2].

Effectiveness and reliability of this method depend on many factors but in particular on the skillful observer and right choice of measuring system.

In the experiment, each test specimen was tested by impact-echo method in two positions exciter – sensor. For each position as an exciter a steel spherical hammer of 70.5 g was used. Hammer is attached to test equipment, so each fall and hit on the body of the test specimen is identical.

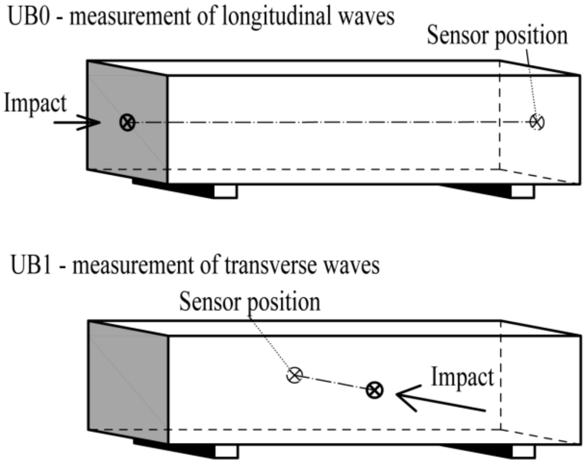

Figure 3. Impact-echo measuring positions.

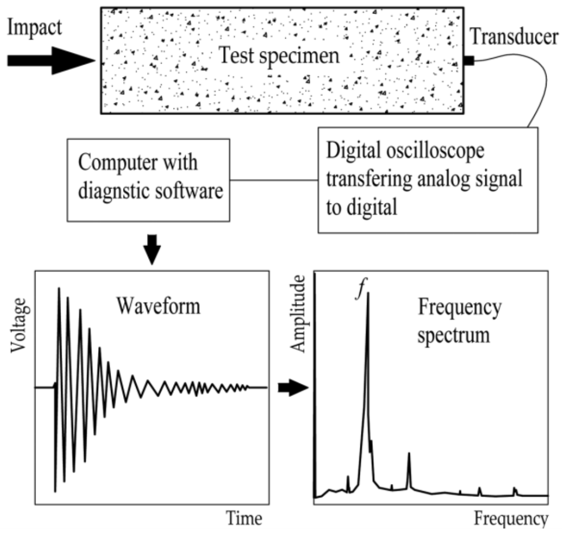

Figure 4. Diagram of measuring process.

The measuring of longitudinal waves is labeled UB0 (see Figure 3. - upper part) and the measurement of transverse waves is labeled UB1 (see Figure 3. - lower part). The diagram of the measuring and Fast Fourier Transform process is shown in Figure 4. As transducer, a piezoelectric sensor is used attached to surface of concrete by beeswax. Signal is recorded by digital oscilloscope Handyscope HS3 with the sampling speed of 10 MHz. For analyzing the signal a TiePie software is used. The waveform is transferred to frequency spectrum by fast furrier transformation [4].

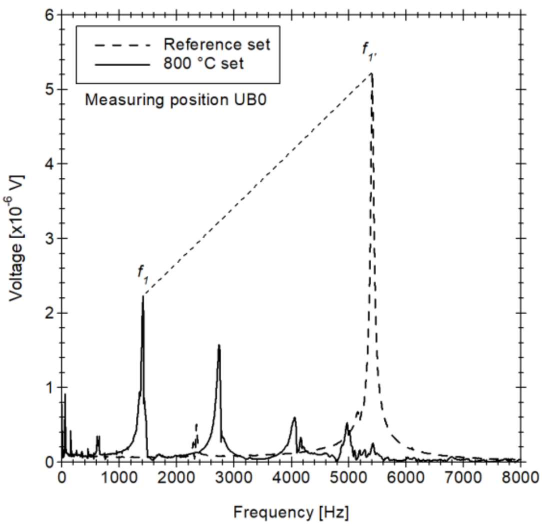

Figure 5. Shift of dominant frequency in longitudinal way of measurement.

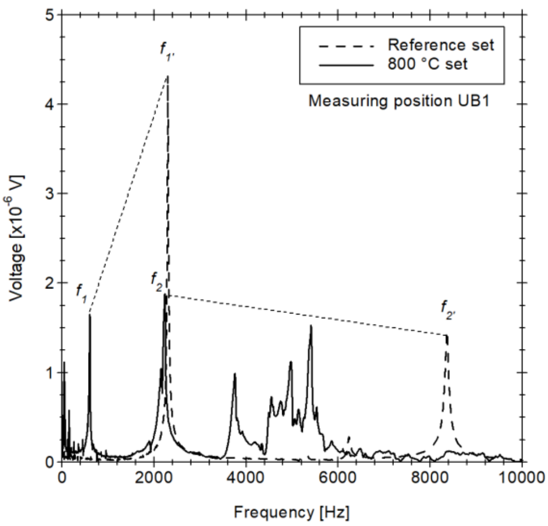

Figure 6. Shift of dominant frequency in transverse way of measurement.

The shift of measured dominant frequency is shown in Figure 5 for longitudinal waves and in figure 6 for transverse waves. In the measuring position UB0, we focus on one dominant frequency f_1. In measuring position UB1, we focus on two dominant frequencies f_1 and f_2.

After degradation of concrete samples by the high-temperature process, the dominant frequencies are shifted from higher to lower frequencies. We compare this change with compressive strength [13] and flexural bending strength [14] which results from destructive tests.

Measured data

On Figure 7. values of dominant frequency in a longitudinal way for mixture A and B are presented. Both mixtures A and B are shifting to lower frequencies as temperature of degradation rises. The significant change appears from 200 to 800 °C for mixture A. Mixture B shows to be more resistance to high-temperature when its downfall appears at 600 °C to 1000 °C. Both mixtures reach lowest frequencies at 1000 °C. Mixture B have a bigger dispersion of measured values than mixture A at 400 °C, 600 °C and 1000 °C. Dominant frequency of both mixtures shows increase of dominant frequency at 1200 °C. This is mainly due to partial sintering, when ceramic bonds start to substitute the damaged hydraulic bonds.

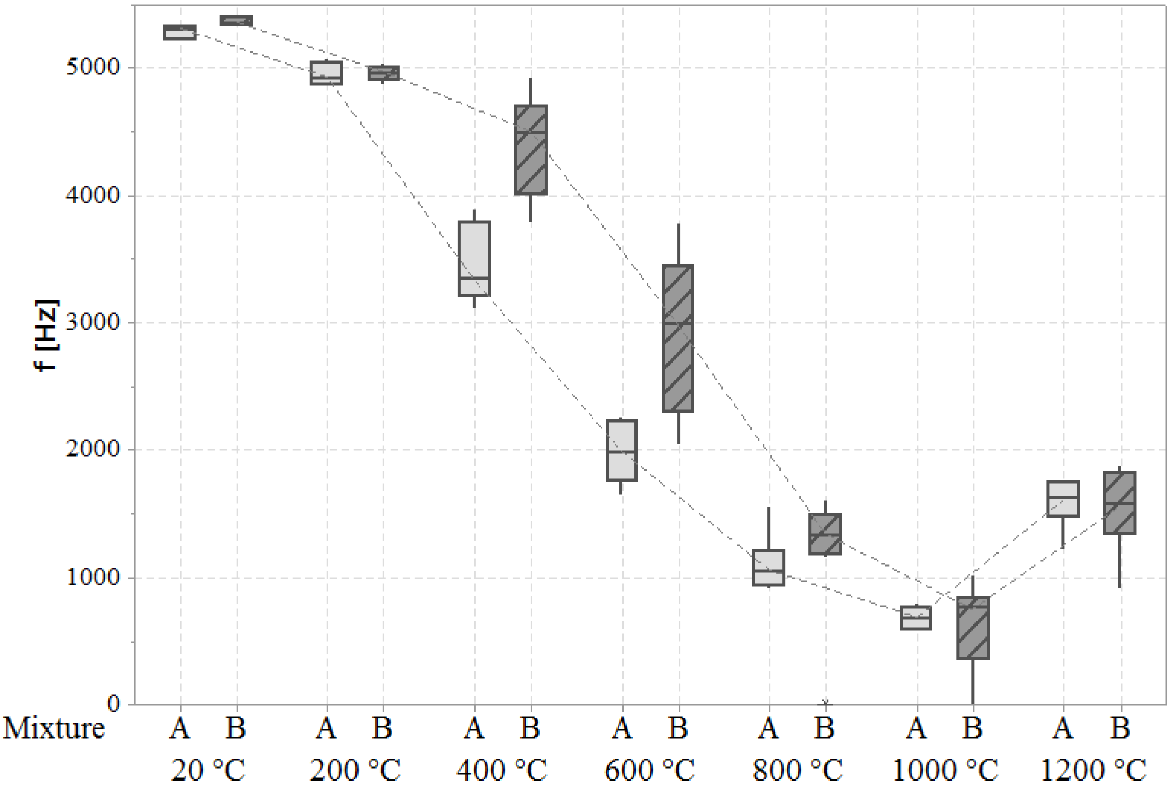

Figure 7. Measured dominant frequencies for mixture A and B in measurement position UB0.

Most rapid changes around 400 and 600 °C are mainly caused by decomposition of portlandite $Ca(OH)_2$ and loosing rest of chemically bounded water. These temperatures were also critical in term of steam pressure rising in pores. In one case, rising of steam pressure led to explosion of test specimen and damaging the furnace, even all of the test specimens were pre-dried. When we compare this results with destructive test, we can see correlation between measured dominant frequency and compressive strength and flexural bending strength. Figure 8. shows, that decrease in strength start already at 200 °C and continues for both mixtures to 1000 °C. At 1200 °C mixture A shows higher values of dominant frequencies and also values of compressive strength and flexural bending strength than mixture B. This is due to smaller fraction of aggregate 8/16 mm. The smaller fraction can absorb more heat energy during burning, and change its structure more easily that bulky 11/22 aggregate, which would take much more energy to change its structure. The granodiorite and quartz sand was used. The granodiorite contained as major components feldspar, quartz and biotite. Feldspar has a melting point about 1170 °C. The quartz has melting point at 1720 °C, but in the presence of alkaline substances (e.g. feldspar, CaO, carbonates, FeO, MgO, etc.), the melting point decreases [15], [16].

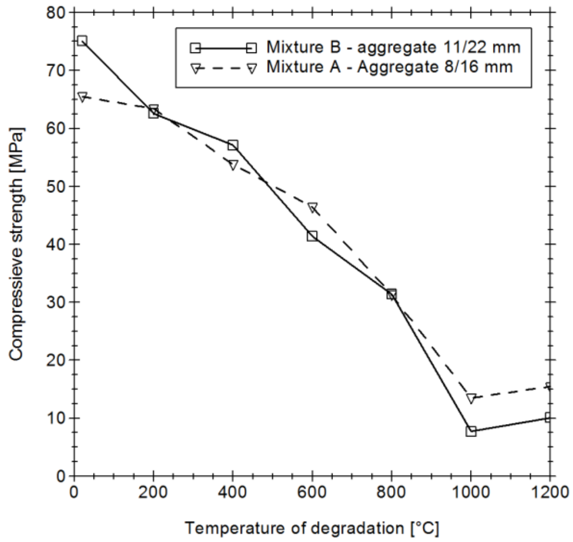

Figure 8. Compressive strength test.

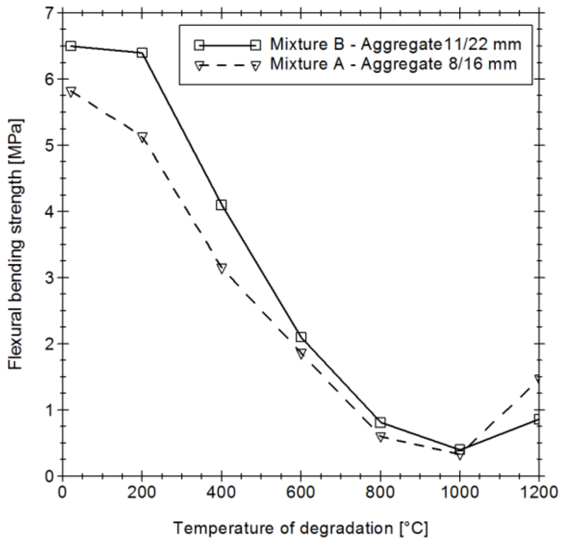

Figure 9. Flexural bending strength test.

The shift of dominant frequencies in a longitudinal way is shown in Figure 10 and shift of two observed frequencies in transverse way is shown in Figure 11. We can see similar trend in both figures. Transverse frequencies f_1 and f_2 envelope longitudinal frequency. Signals of some test specimens were hard to read, and results from longitudinal or transverse waves helped determination of specific frequency. This approach proved to be successful in distinguishing dominant frequency from frequency noise.

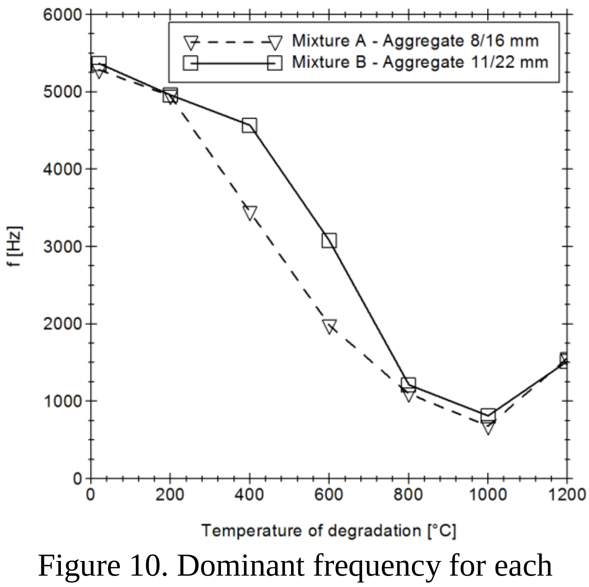

Figure 10. Dominant frequency for each mixture in longitudinal way.

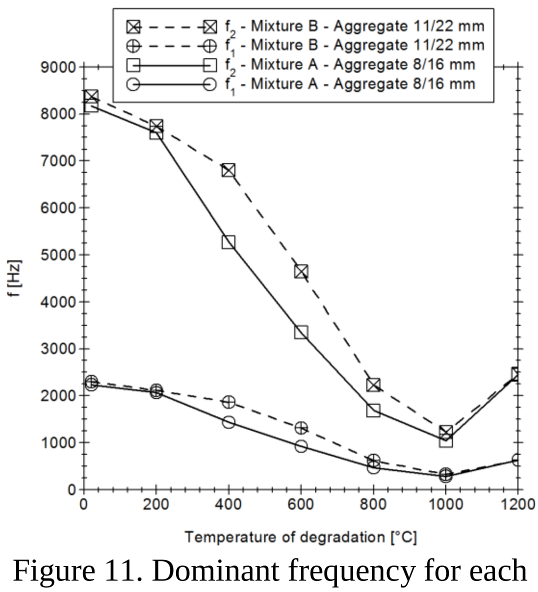

Figure 11. Dominant frequency for each mixture in transverse way.

The significant change in the percentage ratio of flexural bending strength to compressive strength due to the effect of temperature was observed (see Figure 8 and 9). For normal concrete (without steel fibers) the percentage ratio of flexural bending strength to compressive strength is about 8 or 10 % at temperature 20 °C. The higher the temperature had a more destructive influence on flexural bending strength than on compressive strength. Concrete became brittle at high temperature, but at a temperature of 1200 °C the flexural bending strength increased.

Conclusions

This article shows other possibilities of Impact echo method as rapid non-destructive method for evaluating temperature degraded concrete. We've tested test specimens with dimensions of 0.1 x 0.1 x 0.4 m of two mixtures – A with usage of coarse aggregate 8/16 mm and B with usage of coarse aggregate 11/22 mm. Specimens were tested up to 1200 °C by 200°C steps. We observed a shift of dominant frequencies toward the lower frequencies for longitudinal way of measurement and as well for transverse way of measurement. The value of dominant frequencies decreases up to 1000 °C, from this point a slight increase appeared up to 1200 °C. These results are in strong correlation with the values of compressive strength of these samples. Mixture A had flexural bending strength f_{ct} for reference set 5.82 MPa and mixture B had 6.50 MPa. For 1000 °C mixture A had f_{ct} 2.44 MPa with measured dominant frequency 680 Hz in longitudinal way and mixture B had compressive strength of 5.19 MPa with measured dominant frequency 810 Hz. By impact echo results, we can then distinguish different mixture up to 1000 °C. At temperature 1200 °C measured dominant frequencies are 1560 Hz for mixture A and 1520 Hz for mixture B. These measurements show that, for high temperature degraded concrete, Impact-echo results can distinguish level of degradation, on which temperature were specimens tested and thus condition of concrete up to 1200 °C. At 1200 °C melting of basalt and SiO_2 starts and ceramic bonds appears. From these results, we can conclude that Impact echo method is suitable nondestructive method for rapid non-destructive testing of concrete structures and elements affected by fire. However, the testing environment is considered to be a laboratory regulated environment. For specific application in civil engineering for diagnostic purposes, where rise in temperature is much steeper, and temperature last only for brief moment, more experiments had to be done.

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