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DETERMINATION OF THE APPARENT POROSITY LEVEL OF REFRACTORY CONCRETE DURING A SINTERING PROCESS USING AN ULTRASONIC PULSE VELOCITY TECHNIQUE AND IMAGE ANALYSIS

Concrete which undergoes a thermal treatment before (pre-casted concrete blocks) and during (concrete embedded in-situ) its life-service can be applied in plants operating at high temperature and as thermal insulation. Sintering is a process which occurs within a concrete structure in such conditions. Progression of sintering process can be monitored by the change of the porosity parameters determined with a nondestructive test method - ultrasonic pulse velocity and computer program for image analysis. The experiment has been performed on the samples of corundum and bauxite concrete composites. The apparent porosity of the samples thermally treated at 110, 800, 1000, 1300 and 1500 °C was primary investigated with a standard laboratory procedure. Sintering parameters were calculated from the creep testing. The loss of strength and material degradation occurred in concrete when it was subjected to the increased temperature and a compressive load. Mechanical properties indicate and monitor changes within microstructure. The level of surface deterioration after the thermal treatment was determined using Image Pro Plus program. Mechanical strength was estimated using ultrasonic pulse velocity testing. Nondestructive ultrasonic measurement was used as a qualitative description of the porosity change in specimens which is the result of the sintering process. The ultrasonic pulse velocity technique and image analysis proved to be reliable methods for monitoring of micro-structural change during the thermal treatment and service life of refractory concrete.

Key words: ultrasonic pulse velocity; sintering; porosity; concrete for high temperatures; image analysis; mechanical compressive strength.

High-temperature concretes are commonly used as constructive elements and linings of metallurgical furnaces and other plants operating at high temperatures (linings for oil refinery plants, thermal insulation in plants, linings in nuclear power plants, linings in chemical and petrochemical industries, etc.). Benefits from the application of concrete instead of common refractory materials are as follows: simplified building of refractory linings, an economic aspect, *i.e.*, a cheaper process of manufacturing and the possibility of damaged lining reparation [1].

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Mechanical strength of high temperature concrete determines its performance in various applications and is measured in terms of the applied compressive load which concrete can withstand at high temperatures. When concrete is subjected to the increasing compressive load and temperature, the microstructure of the material changes: the apparent porosity increases, pores become bigger and cracks within the structure occur. It results in a loss of strength and composite degradation. The formation of cracks and the increasing porosity decrease density and elastic properties of the material. Therefore, measureing either of these properties can directly monitor the development and change of microstructure. Such thing can be performed by measuring the velocity of ultrasonic pulses (v_p) traveling through the refractory concrete specimen [2,3].

Non-destructive testing method for the investigation of concrete is preferred due to its evident ad-

vantage over conventional compression testing. The method is simple and rapid and there is no need for the destruction of specimen, thus specimen can be used afterwards. The application of ultrasonic pulse velocity technique (UPVT) in non-destructive evaluation of concrete quality has been investigated for decades. This non-destructive testing method has proved to be a useful tool for the inspection of concrete quality in metallurgical furnaces. The evaluation by non-destructive methods of the actual compressive strength of concrete in existing structural elements is based on empirical relations between strength and non-destructive parameters. Furthermore, mechanical strength is in direct relationship with the porosity of concrete and its level of degradation. Manufacturers of UPVT devices usually provide empirical relationships for their own testing system. Such relationships are not suitable for every kind of concrete. Therefore, they need to be calibrated for different mixtures [4,5].

Mentioned mathematical relationships can be derived by means of regression analysis. Numerous data and the correlation relationships between strength (S) and ultrasonic pulse velocity (v_p) of concrete have been proposed [6]. Commonly used formula is:

$$S = a\exp(bv_p) \quad (1)$$

where a and b are empirical parameters determined by the least squares method, S is a compressive strength of concrete and v_p is the ultrasonic pulse velocity of longitudinal waves.

Most factors that influence concrete strength also influence pulse velocity, though not necessarily in the same way or to the same extent. The presence of aggregate affects the relationship between pulse velocity and the compressive strength of concrete: concrete with the highest aggregate content will probably have the highest pulse velocity. Cement type influences pulse velocity and it influences the compressive strength of concrete, too. Higher water content affects the propagation velocity approximately in proportion to the change of the water content in concrete [7]. A review of the literature indicated that ultrasonic waves have been used to predict different properties of concrete: for example, residual properties of thermally damaged concrete [8], initial degree of hydration of concrete [9] and many others [10-13]. This method can also be used to detect the internal defects of concrete such as cracks, delamination, honeycombs, and porosity, *i.e.*, for characterization of microstructural defects [14,15].

UPVT can be accompanied with other non-destructive monitoring method; such is a program for the image analysis. The application of an optical microscope connected to PC with the image analysis program enables entirely new properties to be described: number of pores at the surface, shape and size of pores or cracks, pore roundness, etc. In this paper, the apparent porosity level was monitored after each thermal treatment using Image Pro Plus (IPP) program for the image analysis and the results were correlated with the results of an ultrasonic measurement [16,17].

The apparent porosity of high-temperature composite increases with temperature until certain level is achieved. Namely, sintering process in high-temperature material occurs due to the elevation of temperature: pores tend to spherical shape and start to diminish. Sintering process initiates densification of the material at elevated temperatures (above 1300 °C for an average high-temperature concrete) [18,19].

The goal of this work is to use nondestructive testing method (UPVT) and image analysis (IPP) and their advantages to predict the behavior of concrete submitted to the increase of temperature.

EXPERIMENTAL

Material used in the investigation

Two series of high-temperature concrete samples of different composition (2×60 samples), hereafter indicated as C and B, were investigated. Concrete samples contained different volume fraction and different type of refractory aggregate (Table 1). First type of concrete (B concrete) contained bauxite aggregate and chamotte filler. B concrete can be indicated as commercially available concrete. Another type of concrete (C concrete) was prepared with corundum aggregate and it can be indicated as experimental concrete. Aggregates had different granulations. B and C concretes contained calcium aluminate cement SECAR 70 (Lafarge). The chemical compositions of B and C concretes and calcium aluminate cement (CAC) are given in Table 2.

Methods applied in investigation

The mechanical compressive strength: high-temperature concretes C and B were investigated according to the standard laboratory procedure. Sixty cubic samples of each series (10 cubes for each temperature: 20, 110, 800, 1000, 1300 and 1500 °C) with identical dimensions (10 cm×10 cm×10 cm) were investigated. After 7 days of curing in a climate chamber (at 20 °C), the samples were demoulded and stored for another 21 days under the same conditions as in the climate chamber. After 28 days, the samples were dried at 110 °C for following 24 h. Afterwards, the samples were transferred into an electric furnace and fired at following temperatures: 800, 1000, 1300 and 1500 °C in groups of ten samples and with soak-

Table 1. Mix design parameters for C and B concrete

Parameter	B concrete	C concrete
Cement, %	30	20
Water, %	(12-14 at 100 %)	(12-14 at 100 %)
Aggregate, %	40 + 30	80
Ratio of water to cement	0.6	0.5
Green bulk density, g/cm^3	2.54	2.92
Corundum aggregate size, mm		
- 5 +3	-	28
- 3 + 2	-	22
- 2 + 1	-	28
- 1 + 0.5	-	12
- 0.5+ 0	-	10
Bauxite aggregate size, mm		
- 6 + 4	15	-
- 4 + 1	55	-
- 1 + 0	30	-
Chamotte aggregate size, μm		
+ 74	7.56	-
- 74 + 44	18.23	-
- 44 + 33	17.59	-
- 33 + 23	7.93	-
- 23 + 15	17.53	-
- 15 + 0	31.16	-

Table 2. Chemical composition (wt%) for cement, B and C concrete

Component	Cement	B concrete	C concrete
Al_2O_3	68.85	62.88	93.62
SiO_2	0.107	21.17	0.07
CaO	29.73	8.26	5.97
MgO	0.1368	0.35	0.03
Fe_2O_3	0.058	1.57	0.066
Na_2O	0.285	0.059	0.21
K_2O	0.0078	0.56	-
TiO_2	<0.01	2.03	0.007

ing time of 4 h at each temperature for each group of samples. Each group of concrete specimens was tested for mechanical compressive strength using a conventional laboratory hydraulic pressure device. Same samples were previously tested with UPV method.

The apparent porosity: concrete samples were investigated with an optical microscope (Olympus, CX31-P) accompanied with PC program for the image analysis. The original microscope images were transmitted to the image processor by a color camera. The Image Pro Plus (IPP) program (Materials Pro Analyzer, Version 3.1, Media Cybernetics, Silver Spring, MD, USA) was used in the experiment. Digital photographs of the samples surface were taken after each thermal treatment and after compressive strength testing. Different (damaged and non-damaged) surfaces of the samples were marked with different colors using IPP tools. Thus, higher resolution and sharper difference in damaged and non-damaged surfaces on the specimens could be obtained. Once the appropriate color was selected it was possible to quantitatively measure the ratio and level of damaged and non-damaged areas by means of the image analysis using a statistical approach. The images processed in the analyzer were converted into binary form as white features in front of the black background. The binary images were filtered to reduce, as much as possible, the other features captured together with the target crack images. Enhanced images were ready for quantitative analysis. Program contains a procedure for a systematic collection of the image analysis data by dividing the total observation area into squares. Fol-

lowing a similar procedure, a transparent grid was attached on each plane section before the analysis. IPP basically works on comparing colors of different objects and calculating squares in marked area. At least 10 photographs per sample were analyzed in order to obtain a reliable characterization of the microstructure. The ratio between sample surface area and damaged surface area were calculated for each concrete sample and thus superficial apparent porosity was determined. Example images used in the IPP method are given in Figs. 1 and 2.

Ultrasonic pulse velocity technique (UPVT). A commercial ultrasonic testing instrument of transmission type (PUNDIT plus PC1006, CNS Farnell Ltd., Hertfordshire, England) was used in the experiment. The instrument was equipped with a pulse generator and timing circuit coupled to two transducers (220 kHz) that were positioned manually at opposite ends of each specimen. Each transducer had a 2 mm thick rubber tip to help with overcoming measurement problems due to the roughness of the refractory surface. Vaseline grease was used as the coupling medium. Sixty concrete specimens of each series with identical dimensions (10 cm×10 cm×10 cm) were investigated. For each specimen, the measurements of ultrasonic pulse velocity through the length and thickness on direct transmission disposition were performed. Each test was run at least five times to correctly validate the ultrasonic velocity.

The ultrasonic pulse velocity (v_p) was calculated from the distance between the two transducers and transit time of the pulse measured by an oscilloscope as:

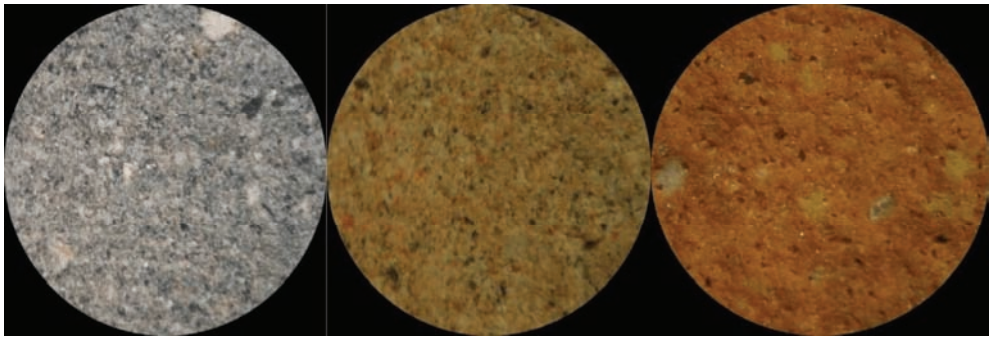
$$v_p = \frac{l}{t} \tag{2}$$

where l is the stress wave path length (m) and t is the transition time (s).

The mechanical compressive strength can be approximately calculated from obtained values of ultrasonic velocity as it is shown by equation (3):

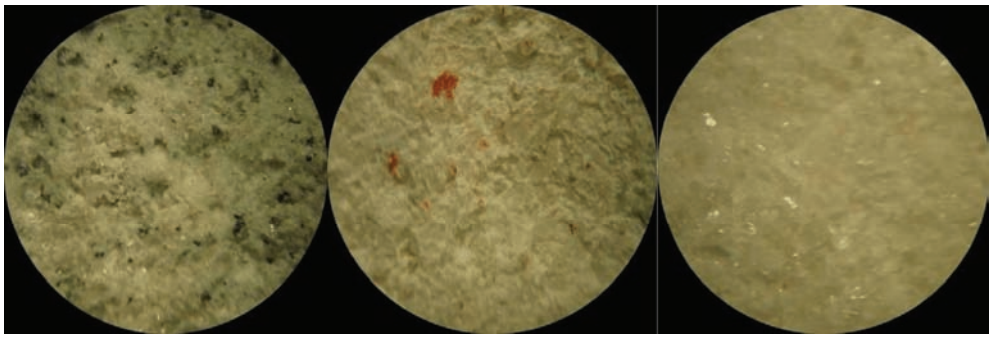
$$S = S_0 \left(\frac{v_p}{v_{p0}} \right)^n \tag{3}$$

where S_0 is the compressive strength before the exposure of the material to the thermal treatment, (MPa); S is the compressive strength after the exposure of the material to the thermal treatment, (MPa), (m/s); v_{p0} is the longitudinal ultrasonic velocity before testing, (m/s), v_p is the longitudinal ultrasonic velocity after testing and n is the material constant (n = 0.488) proposed in the literature and taken as average for both materials [20,21].



(a) (b) (c)

Figure 1. Images of B concrete after thermal treatment at 110 (a), 800 (b) and 1500 °C (c) for IPP analysis.



(a) (b) (c)

Figure 2. Images of C concrete after thermal treatment at 110 (a), 800 (b) and 1500 °C (c) for IPP analysis.

Creep testing was performed on twenty cylindrical C and B concrete samples (50 mm×50 mm); 10 samples for each series of concrete. A hole for the thermo-element (diameter 5 mm) was drilled in the center of each concrete sample. Concrete samples were dried at 110 °C for 24 h and afterwards pre-fired at 800 °C for 4 h. Pre-fired samples were heated at a rate of 5 °C/min from the room temperature up to the testing temperature (1000, 1300 or 1500 °C) in the compressive creep apparatus (Netzsch, Germany) and then submitted to a constant compressive static load (0.2 MPa) at temperatures of 1000, 1300 and 1500 °C, respectively. Each test was conducted for 30 h. During this period the secondary state creep was reached.

If x is a property of the high-temperature concrete which varies during the sintering process and t is the duration of the sintering process then sintering process can be described with the following equation ("power law creep") [22]:

$$x = kt^n \tag{4}$$

where k is time constant and n is constant which describes a mechanism of sintering.

If variable x is a dimensional change, then:

$$\frac{\Delta l}{l_0} = kt^n \tag{5}$$

where $\Delta l = (l - l_0)$ is linear dimensional change of a concrete sample (mm) and l_0 is initial linear dimension of a concrete sample (mm).

Sintering is the process of densification and coarsening of the material which takes place at elevated temperature (generally above 800 °C, but threshold of sintering depends on the properties of a material). Structural changes in the material are caused by elevated temperature and compressive load: pores become spherical and they start to diminish and towards the end of process the smallest pores vanish. The final result is the increase of the material density and the decrease of porosity, which improves the thermo-mechanical properties of the material. In case of the high-temperature concrete, sintering can be investigated during the secondary state creep phase (when creep deformation rate is almost constant and does not depend on time). This relates to isothermal sintering under pressure [22].

SEM images of concrete samples C and B were obtained with microscope SEM JEOL JSM-5300.

RESULTS AND DISCUSSION

The correlation between cold crushing strength, S (MPa), and firing temperature, T (°C), obtained by a destructive method, is presented in Fig. 3.

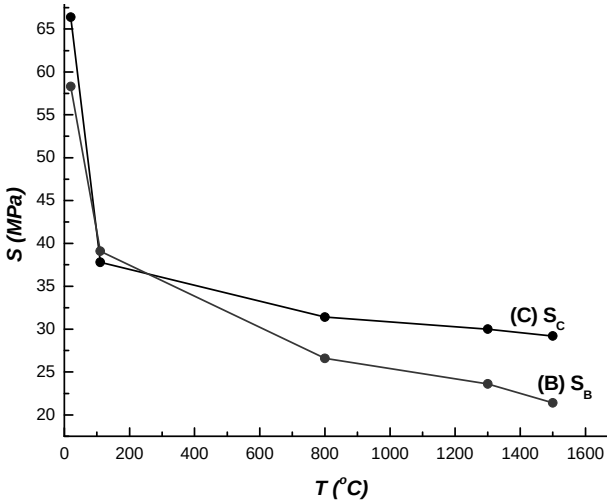


Figure 3. Correlation between cold crushing strength, (S) of concretes B and C and firing temperature, (T).

Figure 4 shows the correlation between the calculated cold crushing strength, S' (MPa), and firing temperature, T (°C).

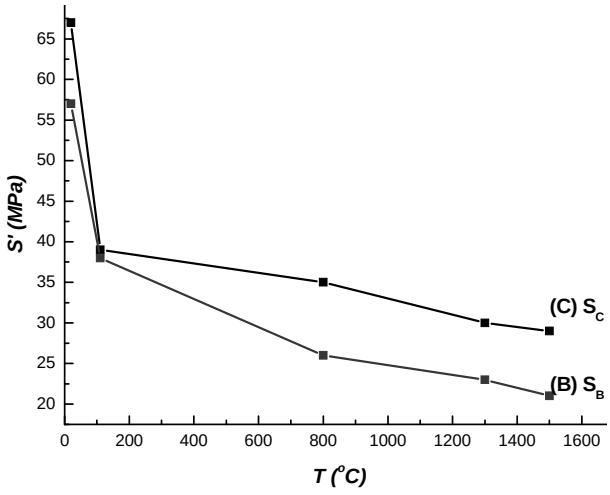


Figure 4. Correlation between calculated cold crushing strength (S') of concretes B and C and firing temperature (T).

The values of cold crushing strength obtained by both methods are approximately the same, as it can be seen in Figs. 3 and 4. This justifies the application of UPVT in the cold crushing strength determination.

Graph presented in Fig. 3 describes cold crushing strength degradation caused by increasing the firing temperature. As it can be seen, C sample has higher initial cold crushing strength (at 20 °C) and also higher final strength (at 1500 °C) than B concrete. The differences in Cold crushing strength values (at 20 and 1500 °C) are 12.2 and 26.7%, respectively. It is evident that C sample shows slower rate of strength degradation than B concrete during thermal treatment from 110 to 1500 °C. Thus, there are differences in

the development of microstructure of these two concrete samples. The differences occur to the better choice of grain-size distribution in the case of C sample. The shrinkage of pores and the improvement of mechanical properties which cannot be expected before 1500 °C is reached due to high refractoriness of both materials. Figure 5 indicates a possible dependence of longitudinal pulse velocity, v_p (m/s), on the firing temperature, T (°C).

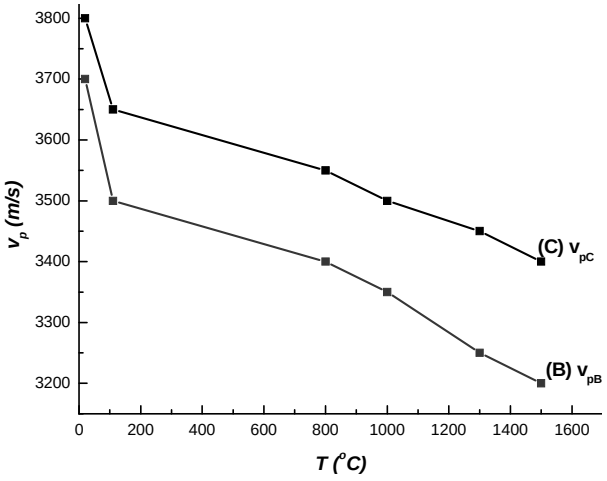


Figure 5. Correlation between longitudinal pulse velocity (v_p) and firing temperature (T).

If graphs in Figs. 3 and 4 were compared to the graph in Fig. 5, the conclusion could be made about the correlation between the composites cold crushing strength and longitudinal pulse velocity: a lower value of cold crushing strength means a slower rate of ultrasound pulse. The reason for decreasing of the cold crushing strength and longitudinal pulse velocity is degradation of concrete microstructure, *i.e.*, the increasing level of porosity. Thus, UPVT method can be used as a means of monitoring the changes in porosity instead of classic laboratory methods (for example, mercury porosimeter), when a precise level of the apparent porosity is not necessary to be known for an experiment.

Figure 6 indicates a possible dependence of the apparent porosity, P (%), obtained by IPP method, on the firing temperature, T (°C).

The apparent porosity of C concrete is lower than the apparent porosity of B concrete at all investigated temperatures (from 20 to 1500 °C) due to better grain-size distribution and better mix design parameters of C concrete. A difference in final apparent porosity value is significant: the apparent porosity of B sample is 16.2% higher than adequate apparent porosity of C sample. This justifies and explains the assumption about the cause of higher degradation of cold crushing strength of B samples, *i.e.*, higher porosity means lower cold crushing strength.

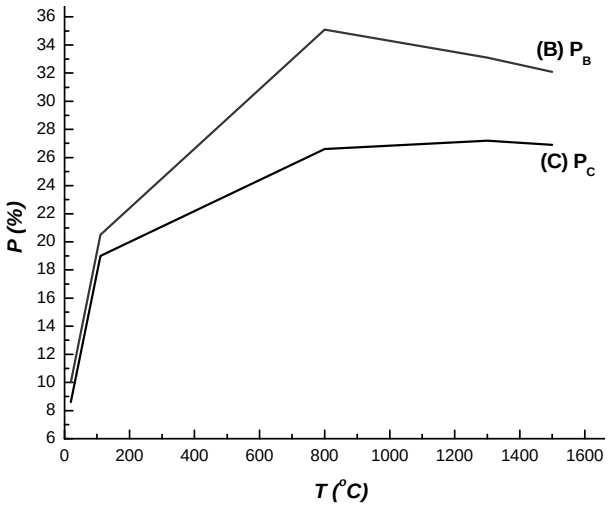


Figure 6. Correlation between apparent porosity (P) and firing temperature (T) for concretes B and C.

A peak on both graphs (in the case of C and B samples) at 800 °C can be noticed in Fig. 6. The peak corresponds to the beginning of the sintering process. Namely, when concrete undergoes a thermal treatment, the sintering process occurs at certain temperature. That usually happens in the temperature interval from 800 to 900 °C. The consequence of sintering would be: decreasing of porosity (material densification), cold crushing strength increasing as a result of lower porosity and higher density, etc. However, in this case, both composites (C and B) have high refractoriness, thus significant decrease of porosity and increment of cold crushing strength are delayed for thermal interval above 1500 °C.

It is to be noted that porosity decreases or maintains almost constant above 800 °C, and the pulse velocity decreases. This indicates that UPVT cannot monitor the porosity to the full extent. Namely, pulse velocity is equally influenced by aggregate size distribution, the presence of structural defects and aggregate agglomerations, as it is effected by the change of porosity.

IPP also provides other parameters such are maximal, minimal and average pore diameter (D_{max}, D_{min} and D_{av}), pore roundness (R) and number of pores (N) situated at the surface. The results are presented in Table 3. According to IPP analysis, the average pore diameter increases from 0.0067 (for C concrete) and 0.003 mm (for B concrete) up to 0.0089 (C) and 0.004 mm (B) at 1300 °C temperature. Afterwards pore shrinkage occurs. Shrinkage is a consequence of the sintering process. B sample has smaller average pore diameter although its apparent poro-

Table 3. Results of Image Pro Plus analysis for B and C concrete samples

T / °C	Concrete									
	B					C				
	D_{max} / mm	D_{min} / mm	D_{av} / mm	N	R	D_{max} / mm	D_{min} / mm	D_{av} / mm	N	R
110	0.056	0.00129	0.003	51	1.07	0.046	0.0042	0.0067	9	1.08
800	0.073	0.00137	0.0035	74	1.12	0.057	0.00448	0.0077	14	1.1
1000	0.079	0.00138	0.0037	81	1.14	0.072	0.0045	0.0084	22	1.13
1300	0.085	0.00138	0.004	80	1.22	0.089	0.0046	0.0089	26	1.138
1500	0.082	0.00130	0.0038	75	1.17	0.084	0.00455	0.0086	24	1.091

sity is higher at all temperatures of investigation. It is a consequence of the choice of aggregate granulation, *i.e.*, in case of B concrete very fine chamotte aggregate (often referred as "chamotte flour") was used as the filler. The ideal pore roundness would be 1.00. For investigated concretes pore roundness is 1.07 to 1.17, which means that pores are almost spherical. *N* is smaller for C sample than in the case of B concrete.

UPVT Method was applied on concrete samples in order to investigate possible structural defects and the presence of pores and to confirm parameters such as cold crushing strength. Regarding specific temperature of investigation, the conclusion can be made on which type of concrete has smaller amount of defects and lower porosity on the specific temperature of the investigation. It is the sample with higher rate of ultra-sound – in this case C concrete sample. Thus, higher porosity of a sample implicates lower ultrasound velocity. A correlation between cold crushing strength and ultrasonic velocity is a reverse correlation between porosity and ultrasonic velocity to certain extent. Regarding the fact that results for porosity are obtained by IPP and the result for mechanical strength with UPVT (compatible with a laboratory method), it can be concluded that using these two methods mentioned the correlation between cold crushing strength and porosity is confirmed and these methods can be used in monitoring and predicting the behavior of a material.

The results of creep investigation are presented in Fig. 7. Creep deformation, $\Delta l/l_0$ (%) in *y*-axis and soaking time, *t* (h) in *x*-axis are indicated on the graph. It can be seen that a linear dimensional change of the sample C at all investigated temperatures is higher than a dimensional change of B concrete. It was expected because average pore diameter of C concrete is higher than in the case of B concrete. There is no significant linear change during creep testing at 1000 °C. At 1300 °C, a small decrease exists on the diagram after 5 h of investigation which might be the result of sintering process initiation. However, the decrease at 1500 °C, registered at 5 (for C) and 10 h (for B), indicates that a sintering process has already begun. This consequently implies that porosity should start to decrease.

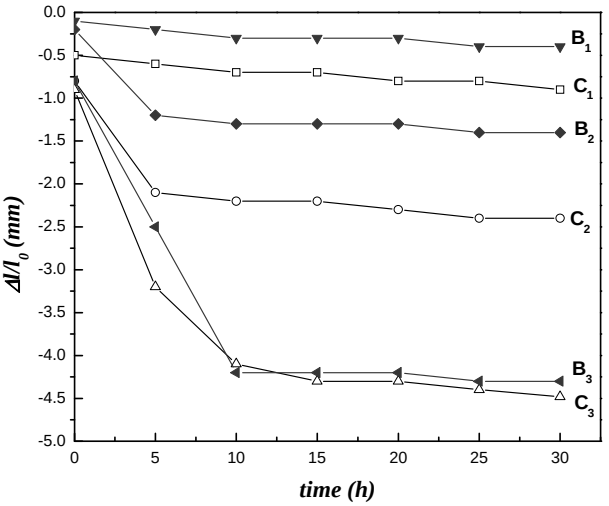


Figure 7. Creep deformation curves of B and C concretes.

The reactions related to the calcium aluminate cement (CAC) explain the observed microstructure evolution as follows: it has been observed that the strength of CAC added castables drops to a minimum after prefiring at around 1100 °C due to the dehydration of the calcium aluminate hydrates which cause changes in the pore size distribution. Above this temperature, the strength tends to increase due to the formation of new minerals caused by the reaction among the components (cement and aggregates) [23].

The results obtained with IPP and UPVT methods are confirmed with SEM images analysis: porosity is higher in the case of B sample, although pores within C sample are bigger (Figs. 8 and 9). In Fig. 8, it can be seen that porosity is clearly visible and higher than in the case of sample C. Large corundum grains surrounded with matrix are visible in Fig. 9. It can also be seen that most of the pores gained spherical shape at 1500 °C, as a result of sintering process.

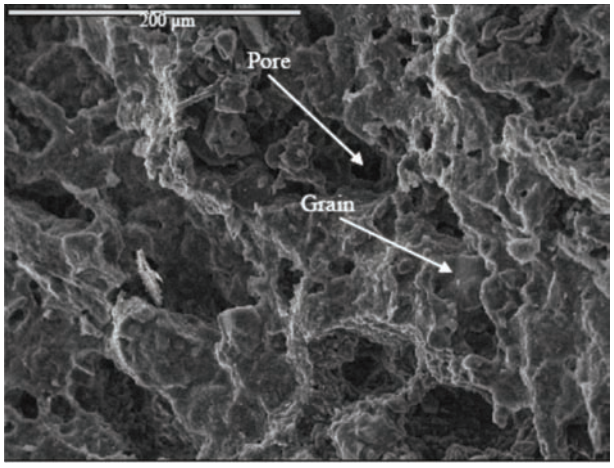


Figure 8. SEM image of B concrete sample heat treated at 1500 °C.

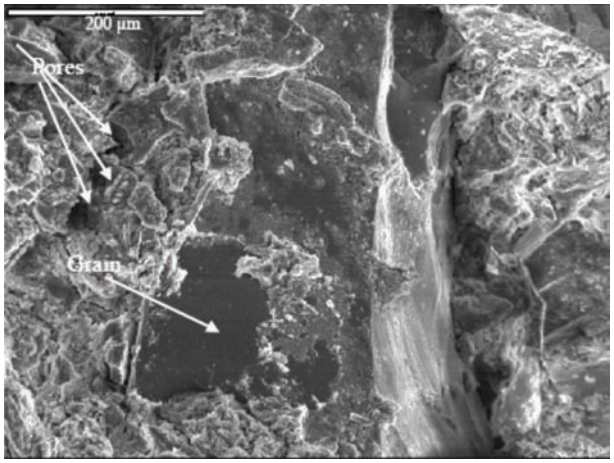


Figure 9. SEM of C refractory concrete heat treated at 1500 °C.

CONCLUSION

The results presented in this paper contribute to the idea of including other testing methods in investigation of mechanical properties of concrete, *i.e.*, non-destructive methods instead of commonly used standard laboratory procedures. Ultrasonic pulse velocity technique is rarely used in the high-temperature concrete investigation. UPVT has number of benefits because it is a non-destructive, simple, fast and reliable method. There is financial benefit in minimizing the number of samples for testing – saving in material and in time. The obtained results and parameters like ultrasonic pulse velocity can be correlated with the results obtained by other methods: the apparent porosity or cold crushing strength. UPVT can be used for the prediction of high-temperature concrete behavior and also in monitoring of the behavior of structural concrete elements and refractory linings of metallurgical furnaces. The advantage of this method is in the fact that there is no necessity to damage the lining of furnace in order to investigate requested parameters. The image analysis provides entirely new and important information about structural damages and surface porosity like, for example, precise diameters of pores, pore roundness and number of pores in a section. As surface damage level is measured, the results could be useful for the prediction of the sample behavior during further testing or application in a metallurgic furnace or in thermal insulation.

The results of UPVT and IPP showed that experimental refractory concrete (in text referred as C – corundum concrete) possesses better mechanical and thermal characteristics than commercially available bauxite concrete (B) due to its better aggregate properties and granulation and better mix parameter design.

Nomenclature

a, b - Empirical parameters determined by the least squares method;
D_{av} - Average pore diameter, mm;
D_{max} - Maximal pore diameter, mm;
D_{min} - Minimal pore diameter; mm;
k - Time constant which describes a mechanism of sintering;
l - The stress wave path length, m;
Δl - Linear dimensional change, mm;
l_0 - Initial linear dimension, mm;
n - The material constant (n = 0.488);
N - Number of pores situated at the surface.
R - Pore roundness;
S - Compressive strength, MPa;
S_0 - Compressive strength before the exposure of the material to the thermal treatment, MPa;
t - The transit time of ultrasound, s;
v_p - The ultrasonic pulse velocity of longitudinal waves, m/s;
v_{p0} - The longitudinal ultrasonic velocity before testing, m/s.

Abbreviations

IPP - Image Pro Plus;
UPVT - Ultrasonic Pulse Velocity Technique.

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NAUČNI RAD

ODREĐIVANJE VELIČINE PRIVIDNE POROZNOSTI VATROSTALNOG BETONA U TOKU PROCESA SINTEROVANJA POMOĆU METODE BRZINE ULTRAZVUKA I ANALIZE SLIKE

Beton koji prolazi kroz termički tretman pre (prefabrikovani betonski blokovi) i u toku (beton ugrađen na licu mesta) svog eksploatacionog perioda može se koristiti u visokotemperaturnim postrojenjima ili kao termički izolator. U takvim uslovima u strukturi betona dolazi do procesa sinterovanja. Napredovanje procesa sinterovanja se može registrovati praćenjem promene parametara poroznosti koji su određeni nedestruktivnom metodom brzine ultrazvuka i računarskim programom za analizu slike. Ispitivanje je sprovedeno na uzorcima korundnih i boksitnih betonskih kompozita. Prividna poroznost uzoraka koji su termički tretirani na 110, 800, 1000, 1300 i 1500 °C je najpre određena standardnom laboratorijskom procedurom. Parametri sinterovanja su određeni iz rezultata dobijenih ispitivanjem tečenja. Kada je uzorak izložen povišenoj temperaturi i naponu na pritisak dolazi do smanjenja čvrstoće i degradacije materijala. Mehanička svojstva ukazuju i prate promene u mikrostrukturi. Nivo površinskih oštećenja uzoraka nakon termičkog tretman je određen pomoću Image Pro Plus programa. Mehanička čvrstoća je procenjena pomoću ultrazvučnih ispitianja. Nedestruktivno ultrazvučno merenje je upotrebljeno kao kvalitativan opis promene poroznosti uzoraka koja je posledica procesa sinterovanja. Metoda brzine ultrazvuka i metoda analize slike su se pokazale kao pouzdane metode za monitoring mikro-strukturnih promena u toku termičkih tretmana ili eksploatacije betonske obloge.

Ključne reči: brzina ultrazvuka; sinterovanje; poroznost; visokotemperaturni betoni; analiza slike; mehanička pritisna čvrstoća.