EVALUAREA BETOANELOR CA MATERII PRIME CONVENȚIONALE ŞI RECICLATE, PENTRU APLICAȚII DE TEMPERATURĂ ÎNALTĂ
EVALUTION OF CONCRETES WITH STANDARD AND RECYCLED RAW MATERIALS FOR HIGH TEMPERATURE APPLICATION

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Concrete undergoing thermal treatment before and during life-service can be applied as building material for thermal insulation in high-temperature plants. When such concretes are designed with secondary raw materials they show satisfying performances. Sintering and microstructural changes occur within concrete with increasing temperature. Change progression can be monitored by measuring compressive strength and porosity with destructive and non-destructive tests (ultrasonic pulse velocity technique, image analysis). Experiment has been performed on standard, corundum concrete and recycled, bauxite concrete. Samples were thermally treated from 110 to 1500ºC. Destructive tests were used in compressive strength and porosity investigation. Non-destructive tests were performed in order to compare results. Creep testing was conducted to prove sintering process. Results showed that recycled concrete has equal properties as standard concrete.

Betoanele tratate termic înainte şi pe durata de exploatare pot fi utilizate ca materiale termoizolante în instalații de temperatură înaltă. Atunci când betoanele termoizolante de înaltă temperatură sunt obținute cu materiale secundare, acestea trebuie să îndeplinească cerințe specifice celor convenționale. Procesele de sinterizare şi modificările structurale se defăşoară la temperatură ridicată, de expunere a betonului. Evoluția modificărilor structurale poate fi monitorizată prin măsurarea rezistenței la compresiune şi a porozității prin metode distructive şi nedistructive (viteza de propagare a US, analiza microscopică). Partea experimentală a fost realizată cu betoane corindonice standard şi betoane cu bauxită reciclată. Probele au fost tratate termic, după o curbă de ardere de la 110 la 1500ºC. Rezistența la compresiune şi porozitatea s-au determinat cu metode distructive, iar testele nedistructive au fost folosite în scop comparativ. Pentru aprecierea procesului de sinterizare s-a efectuat încercarea de fluaj. Rezultatele încercărilor au arătat că proprietățile betonului reciclat sunt similare cu cele ale betonului convențional.

Keywords: *ultrasonic pulse velocity, sintering, high-temperature concrete, image analysis, recycling*

1.Introduction

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]. Following the request for environmental safety and sustainability of natural materials resources, there is tendency and necessity for developing refractory concretes partly of completely based on recycled materials.

What determines the performances of high-temperature concrete is mechanical strength in its various applications. It 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, the 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, measuring 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 simplicity. It is 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 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,

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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 [4,5]. Mentioned mathematical relationship is the correlation between strength (*f*) and ultrasonic pulse velocity (v_p) of concrete. Commonly used formula is: [6].

$$f = a \cdot \exp(b \cdot v_p) \qquad (1)$$

where: a and b are empirical parameters determined by the least squares method, *f* is the 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. For example: the presence of aggregate affects the relationship between pulse velocity and the compressive strength of concrete: concrete with the highest aggregate content have the highest pulse velocity [7].Cement type influences pulse velocity and the compressive strength of concrete [8].Higher water content affects the propagation velocity approximately in proportion to the change of the water content in concrete [9]. A review of the literature data indicated that ultrasonic waves have been used to predict different properties of concrete: residual properties of thermally damaged concrete [10], initial degree of hydration of concrete [11] and many others [12, 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].

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 ºC for an average high-temperature concrete) [17, 18].

The goal of this work is to use nondestructive testing method (UPVT) and image analysis (IPP) and thus to compare the behavior of standard high-temperature concrete with high-temperature concrete based on recycled aggregates.

2. Description of Method of Work

Two series of high-temperature concrete samples of different composition (2 x 60 samples), hereafter indicated as SC and RC, were investigated. Concrete samples contained different volume fractions and different type of refractory aggregate (Table 1). RC concrete contained recycled bauxite aggregate from old crushed bricks and chamotte filler. SC concrete was prepared with corundum aggregate and it can be indicated as commercial/standard concrete. Aggregates had different granulations. RC and SC concretes contained calcium aluminate cement SECAR 70 (Lafarge). The chemical compositions of RC and SC concretes and calcium aluminate cement (CAC) were obtained by atomic absorption spectrophotometer AAS Analyst 300 and are given in Table 2.

Table 1

Mix design parameters for SC and RC concrete
Compoziţia amestecurilor de beton de temeperatură înaltă – convenţional SC şi reciclat RC

	RC concrete	SC concrete
Cement/*Ciment* (%)	30	20
Water/*Apă* (%)	13	13
Aggregate/*Agregat* (%)	40 + 30	80
Water to cement ratio *Raport apă/ciment*	0.7	0.6
Bulk density (g/cm^3) *Densitatea aparentă*	2.58	2.96
Corundum (%)		
- 5 +3 (mm)		30
- 3 + 2 (mm)		20
- 2 +1 (mm)		26
- 1 + 0,5(mm)		14
- 0,5+ 0(mm)		10
Bauxite (%)		
- 6 + 4(mm)	15	
- 4 + 1(mm)	50	
- 1 + 0(mm)	35	
Chamotte (%)		
+ 74 (μm)	7.58	
- 74 + 44 (μm)	18.21	
- 44 + 33 (μm)	16.59	
- 33 + 23 (μm)	8.95	
- 23 + 15 (μm)	18.51	
- 15 + 0 (μm)	30.16	

Table 2

Chemical composition (wt%) for cement, RC and SC concrete
Compoziţia cimentului folosit la obţinerea betoanelor SC şi RC

(%)	Cement	RC con.	SC con.
Al_2O_3	68.8	62.8	93.7
SiO_2	0.112	21.25	0.07
CaO	29.69	8.24	5.91
MgO	0.138	0.37	0.03
Fe_2O_3	0.058	1.57	0.066
Na_2O	0.286	0.059	0.21
K_2O	0.0077	0.5	-
TiO_2	<0,01	2.09	0.007

The concrete mixtures were prepared and cured accordingly to standard (SRPS B.D8.300). Concretes were mixed for 8 minutes in laboratory RILEM-cem mixer and, afterwards, shaped in different moulds depending on test applied afterwards.

The mechanical compressive strength (MCS) was investigated on high-temperature concretes SC and RC according to the standard laboratory procedure (SRPS U.M1.005). Sixty cubic samples of each series (10 cubes for each temperature: 20, 110, 800, 1000, 1300 and 1500 ºC) with identical dimensions (10x10x10 cm) were investigated. After 7 days of curing in a climate chamber (at 20 ºC and 60 % relative humidity), 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 ºC for following 24 hours. Afterwards, the samples were transferred into an electric furnace and fired at following temperatures: 800, 1000, 1300 and 1500 ºC in groups of ten samples and with soaking time of 4 hours at each temperature for each group of samples. Each group of concrete specimens was tested for MCS using a conventional laboratory hydraulic pressure device. Same samples were previously tested with UPV method. The apparent porosity of concrete samples was investigated with an optical microscope (Olympus, CX31-P) accompanied with PC program for the image analysis and with mercury porosimeter on 10x10x10 cm samples.

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, so higher resolution and sharper difference in damaged and non-damaged surfaces on the specimens could be obtained. Thus 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. Program contains a procedure for a systematic collection of the image analysis data by dividing the total observation area into squares. 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. Examples of the images used in the IPP method are given in Figures 1 and 2.

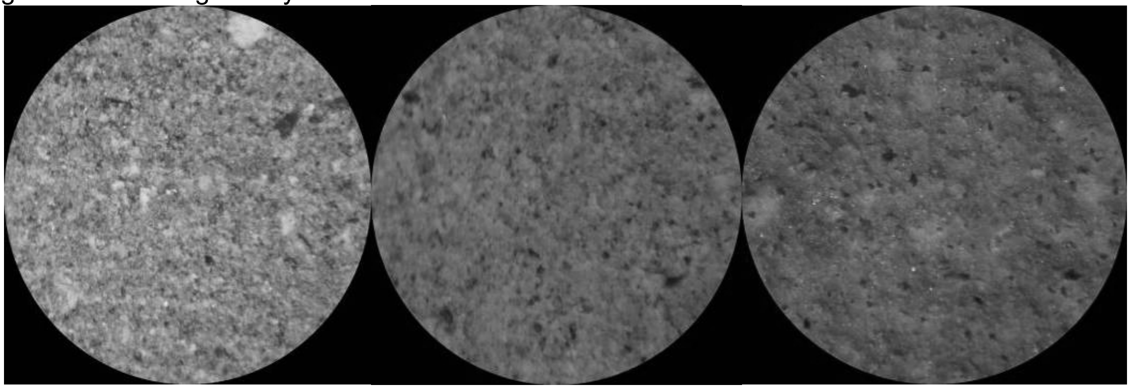

Fig. 1- Images of RC concrete after thermal treatment at 110, 800 and 1500 ºC for IPP analysis / *Imagini de microscopie optică ale structurii betonului RC după tratamentul termic la 110, 800 şi 1500 ºC, conform programului IPP.*

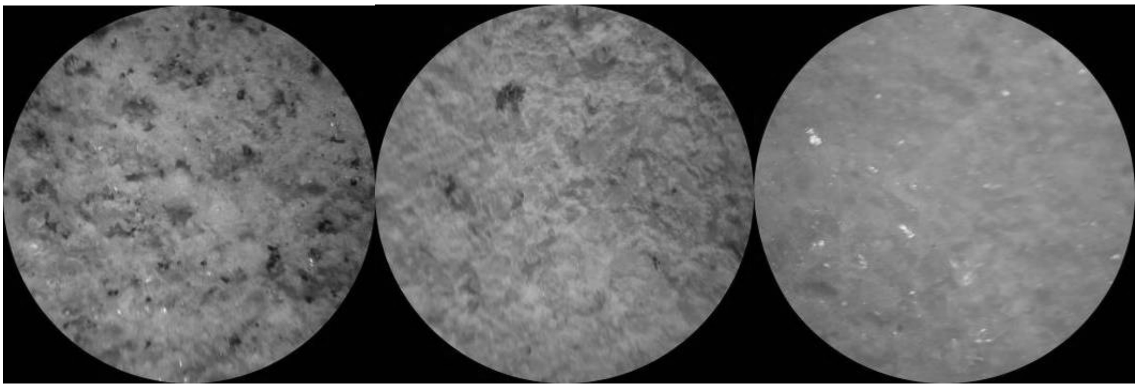

Fig. 2 - Images of SC concrete after thermal treatment at 110, 800 and 1500 ºC for IPP analysis / *Imagini de microscopie optică ale structurii betonului SC după tratamentul termic la 110, 800 şi 1500 ºC, conform programului IPP.*

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 serie with identical dimensions (10x10x10 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 transit time (sec).

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

$$f' = f_0' \left(\frac{v_p}{v_{p0}} \right)^n \tag{3}$$

where: f'_0 is the compressive strength before the exposure of the material to the thermal treatment, (MPa); f' 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 [19, 20].

Refractoriness was investigated on prismatic-shaped samples (10x10x45 mm) in standard Netzsch furnace PCE 482 for refractoriness testing. Temperature increasing rate was 4ºC/min.

Creep testing was performed on twenty cylindrical SC and RC concrete samples (50x50 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 ºC for 24 hours and afterwards pre-fired at 800 ºC for 4 hours. Pre-fired samples were heated at a rate of 5 ºC/min from the room temperature up to the testing temperature (1000, 1300 or 1500 ºC) 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 ºC, respectively. Each test was conducted for 30 hours. 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") [21].

$$x = k \cdot t^n \tag{4}$$

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

If variable x is a dimensional change, then:

$$\frac{\Delta l}{l_0} = k \cdot t^n \tag{5}$$

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 ºC, but threshold of sintering depends on the properties of a 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). Thus, creep diagram is used to prove that sintering occurred [21].

SEM images of concrete samples SC and RC were obtained with microscope SEM JEOL JSM-5300. X-ray powder diffraction patterns of concrete samples were obtained using a Philips PW-1050 diffractometer with λCu-K_α radiation and stop/time scan mode of 0.05 º/1s.

3. Results, interpretation and discussion

In Figure 3 XRD patterns of concretes RC and SC (at T = 1500 ºC) are presented. By means of XRD method the following phases were found: α-Al_2O_3 corrundum, mulite, hibonite in RC sample (after firing at 1500 ºC); and hibonite and corundum in SC sample (after firing at 1500 ºC).

Figure 4 shows the correlation between the measured mechanical compressive strength (MCS) determined by destructive method - f (MPa) and firing temperature - T (ºC), as well as the correlation between the calculated mechanical compressive strength (determined by UPVT) - f' (MPa) and firing temperature - T (ºC)

The values of MCS obtained by both methods are approximately the same, as it can be seen in Figure 4. This justifies the application of UPVT in the MCS determination. Graph presented in Figure 4. describes MCS degradation caused by increasing of the firing temperature. As it can be seen, SC sample has higher initial MCS (at 20 ºC) and also higher final strength (at 1500 ºC) than RC concrete.

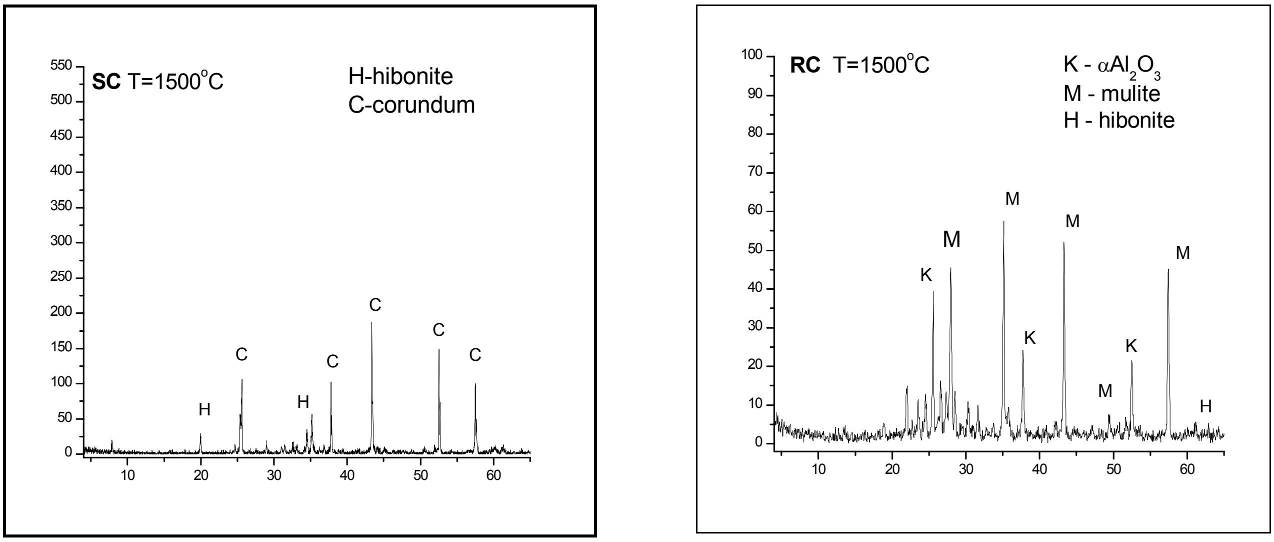

Fig. 3 - XRD patterns of RC and SC samples at 1500 °C / *Difractograme RX ale probelor RC şi SC, tratate termic la 1500 °C.*

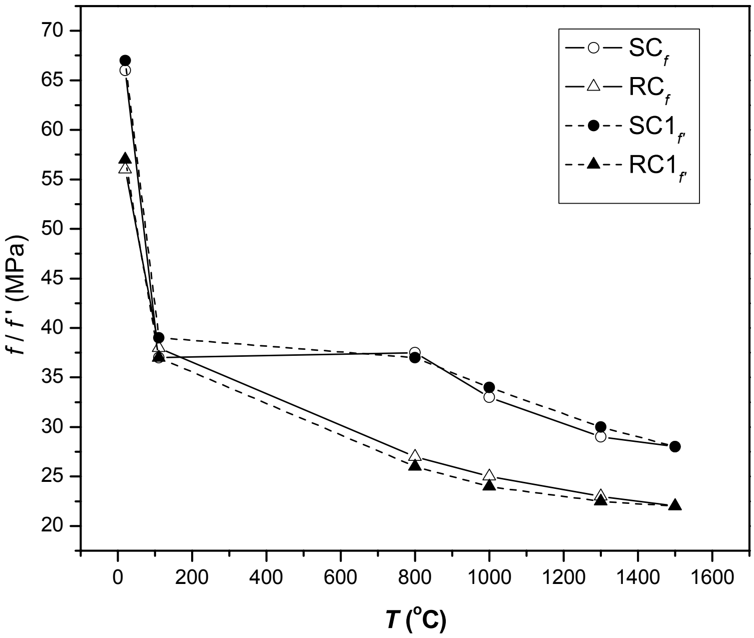

Fig. 4 - Correlations between MCS, (*f*) and firing temperature (*T*) and between calculated MCS (*f'*) and firing temperature for concretes RC and SC / *Compararea valorilor rezistenţei la compresiune (f) determinate distructiv şi a rezistenţei la compresiune de calcul, (f'), a probelor de beton RC şi SC, în funcţie de temperatura de ardere (T).*

This was expected due to the quality of the raw material, i.e. aggregates. Corundum has higher compressive strength than bauxite. The differences in MCS values (at 20 and 1500 °C) are 12 and 26 %, respectively. Considering the fact that bauxite used in experiment is actually recycled material (crushed used bauxite brick) which lost some of its original strength through its service-life and additional crushing, this difference in MCS is rather acceptable for concrete application. Strengths above 60 and 50 MPa categorize investigated concretes in building concretes group with normal to high MCS. Investigated concretes will be used for thermal insulation linings and MCS values are even above standard expectations for such application. Namely, it isn't required that refractory concretes have high MCS on normal temperature. At high temperature (1500 °C) MCS is 28 and 22, respectively. That means that even on extreme temperatures investigated concretes and not losing its MCS completely and there is no melting nor seggregation of used raw materials. SC sample shows slower rate of strength degradation than RC concrete during thermal treatment from 110 °C to 1500 °C. Thus, there are differences in the development of microstructure of these two concrete samples. There is, probably, some amount of amorphous phase formed within microstructure of RB which causes more rapid properties degradation than in case of SC. Higher refractoriness of SC confirms this hypothesis. The shrinkage of pores and the improvement of mechanical properties can not be expected before 1500 ºC is reached due to high refractoriness of both materials.

A lower value of MCS means a slower rate of ultrasound pulse. The reason for decreasing of the MCS 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 5. indicates the apparent porosity - *P'* (%), obtained by IPP and apparent porosity - *P* (%) obtained by means of porosimeter in correlation with firing temperature, *T* (ºC).

Higher porosity of RC concrete is consequence of application of recycled aggregates. Although the filler is used and mix design of RC is better than granulometry of SC (more fractions were used in case of RC concrete) porosity is still higher (difference in final apparent porosity is 16 %). This can be explained by increased porosity of recycled-bauxite aggregate in comparison with corundum aggregate.

Namely, corundum aggregate is likely to be porous. Recycled concrete, thus absorbs more water. The apparent porosity of SC concrete is lower than the apparent porosity of RC concrete at all investigated temperatures (from 20 to 1500 ºC). Such difference in porosity of RC and SC justifies and explains the assumption about the cause of higher degradation of MCS of RC samples, i.e. higher porosity means lower MCS. A peak on both graphs (in case of SC and RC samples) at 800 ºC can be noticed in Figure 5. The peak precisely corresponds to the early beginning of the sintering process. Namely, when concrete undergoes a thermal treatment, the initial sintering process occurs at certain temperature. That usually happens in the temperature interval from 800 to 900 ºC. The consequence of sintering would be: decreasing of porosity (material densification), MCS increasing as a result of lower porosity and higher density, etc. However, in this case, both composites (SC and RC) have high refractoriness, thus significant decrease of porosity and increment of MCS are delayed for thermal interval above 1500 ºC.

Porosity investigated by IPP method is also given in Figure 5. The porosity values are slightly lower than values obtained by mercury porosimeter, but diagram paths are parallel. Reason for such difference is that IPP method "records" pores which are visible on superficial area of a sample: superficial pores and pores visible within those pores. IPP is not capable of

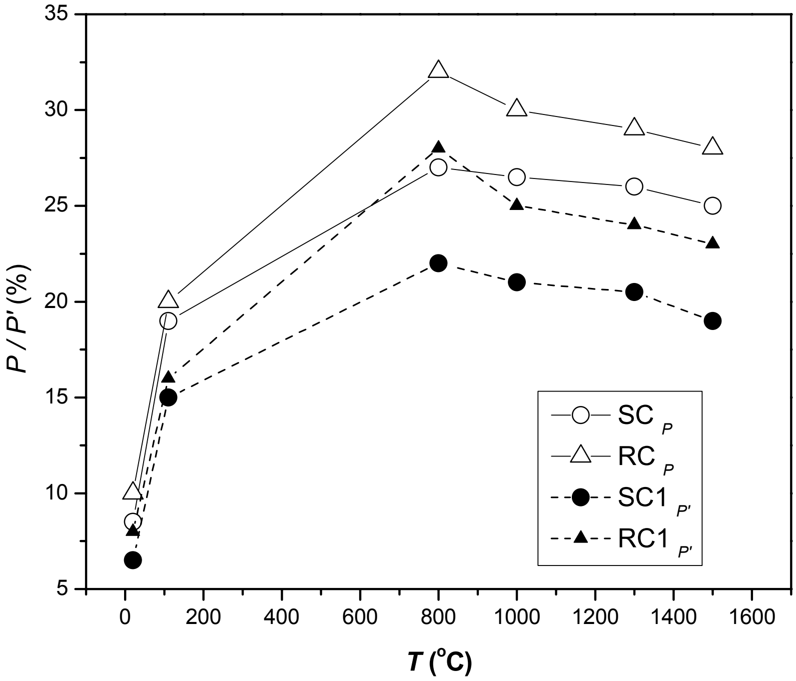

Fig. 5 - Correlation between apparent porosity, (*P and P'*) and firing temperature, (*T)* for concretes RC and SC.
Corelarea porozității aparente (P şi P') cu temperatura de ardere (T) a betoanelor RC şi SC.

indicating possible existence of closed, internal pores. IPP also provides other parameters such are maximal, minimal and average pore diameter (D_{max}, D_{min}, D_{av}), pore roundness (R).

The results are presented in Table 3. According to IPP analysis: the average pore diameter increases from 0.0067 mm (for SC concrete) and 0.003 mm (for RC concrete) up to 0.0089 mm (SC) and 0.004 mm (RC) at 1300 ºC temperature. Afterwards pore shrinkage occurs. Shrinkage is a consequence of the sintering process. RC sample has smaller average pore diameter although its apparent porosity is higher at all temperatures of investigation. It is a consequence of the choice of aggregate granulation, i.e. in case of RC concrete very fine chamotte aggregate (often referred as "chamotte flour") was used as the filler. Porosity is higher because recycled bauxite aggregate is porouse (more porous than corundum aggregate). The ideal pore roundness would be 1.00. For investigated concretes pore roundness is 1.05 to 1.16, which means that pores are almost spherical. Above 1300 ºC pores start gaining spherical appearance due to the sintering process. Pores of RC concrete have more spherical shape than pores of SC, due to the usage of filler. For the same reason average pore diameter of RC concrete is smaller than in case of SC.

Table 3

Results of Image Pro Plus analysis for RC and SC concrete samples / *Caracterizarea porilor după dimensiune (diametrul D_{max}, D_{min}, D_{av}) şi după formă (R) dată de programul IPP, pentru betoanele SC şi RC*

T (ºC)	RC				SC			
	D_{max} (mm)	D_{min} (mm)	D_{av} (mm)	R	D_{max} (mm)	D_{min} (mm)	D_{av} (mm)	R
110	0.056	0.00129	0.003	1.05	0.046	0.0042	0.0067	1.08
800	0.073	0.00137	0.0035	1.18	0.057	0.00448	0.0077	1.12
1000	0.079	0.00138	0.0037	1.11	0.072	0.0045	0.0084	1.15
1300	0.085	0.00138	0.004	1.12	0.089	0.0046	0.0089	1.16
1500	0.082	0.00130	0.0038	1.07	0.084	0.00455	0.0086	1.11

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 MCS. 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 SC concrete sample. Thus, higher porosity of a sample implicates lower ultrasound velocity. A correlation between MCS 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.

Refractoriness for RC is SK 20 (T = 1540 ºC) and for SC is SK 34 (T = 1755 ºC). The results of creep investigation are presented in Figure 6. Creep deformation, $\Delta l/l_0$ (%)in y-axis and soaking time, t (h) in x-axis are indicated on the graph (Figure 6). It can be seen that a linear dimensional change of the sample RC at all investigated temperatures is higher than a dimensional change of SC concrete. It was expected because average pore diameter of SC concrete is higher than in the case of RC concrete and because RC has lower refractoriness. There is no significant linear change during creep testing at 1000 ºC. At 1300 ºC a small decrease exists on the diagram after 5 hours of investigation which might be the result of sintering process initiation. However, the decrease at 1500 ºC registered at 5 hours (for C) and 10 hours (for B) indicates that a sintering process has already begun. This consequently implies that porosity started decreasing.

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 ºC 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) [22].

Figures 7. and 8. show SEM microphotographs of concrete samples. As it is well knows concrete is complex, heterogeneous, multiphase material which is often considered to be three-phase composite structure. Its structure includes aggregate particles, the cement paste matrix in which they are dispersed and the interfacial transit zone around aggregate particles and cement paste. Concrete often exhibits random microstructure of different length scales ranging from nanometers scale to macroscopic decimeters scale. According to the microstructure analysis aggregate particles, several mm in size are surrounded with fine matrix composed of micron sized particles. Cement paste, fine and coarse

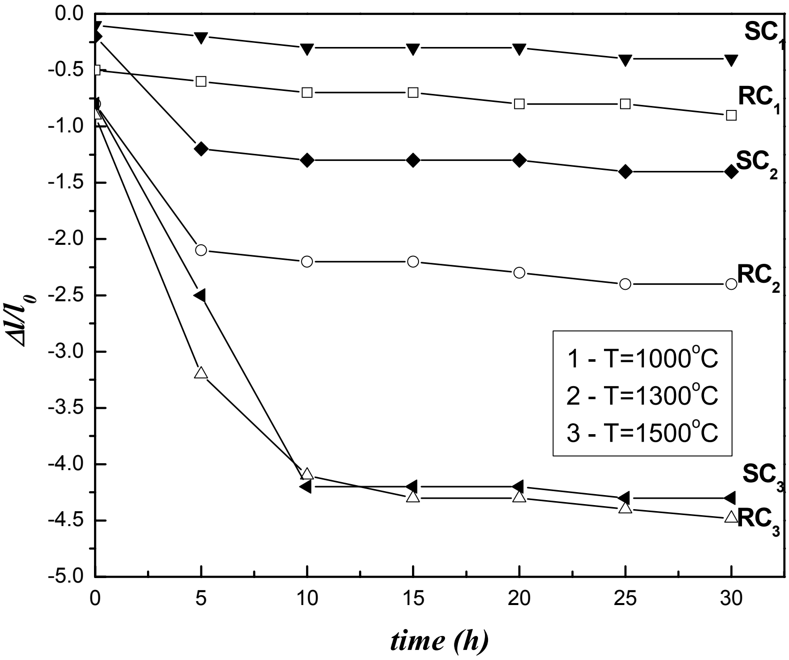

Fig 6 - Creep curves of RC and SC concretes / *Deformația la încercarea de fluaj a betoanleor RC şi SC.*

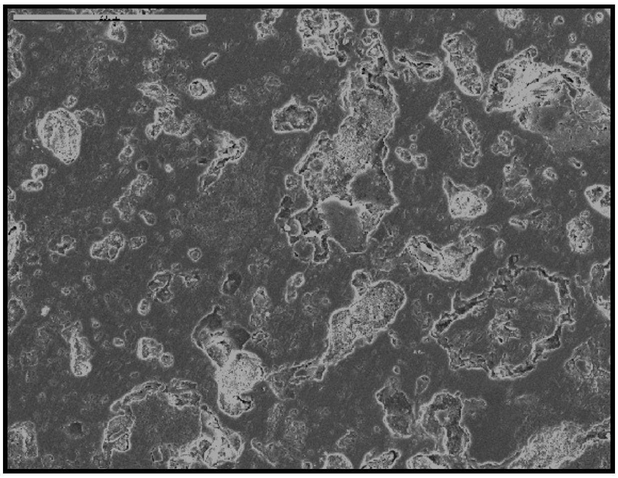

Fig 7 - SEM image of RC concrete sample thermic treated at 1500 °C (bar = 200µm) / *Imagine SEM a probei de beton RC tratate termic la 1500 °C.*

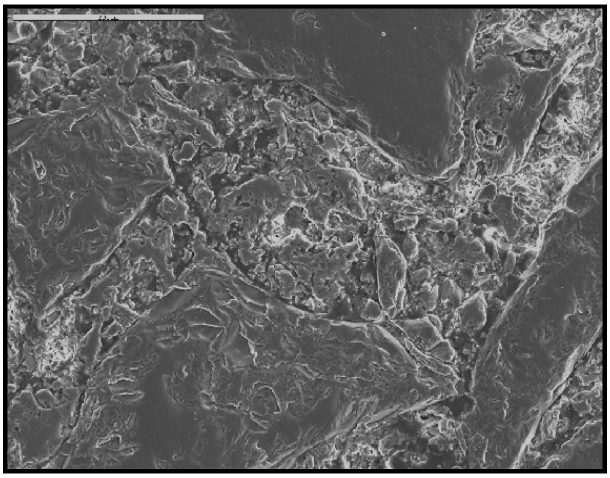

Fig 8 - SEM of SC refractory concrete thermic treated at 1500 (bar = 200µm) / *Imagine SEM a probei de beton SC tratate termic la 1500 °C.*

aggregates, with range of sizes and shapes, as well as crack structures and pores of various sizes were notices on photos. It should be noticed that the structure of porosity in concrete strongly influences its properties. Their structure is related to the original packing of the cement and aggregate particles and to the water-to-solids ratio, etc. Sources of porosity in concrete includes: gel pores, smaller capillary pores, larger capillary ores, large voids, porosity associated with paste-aggregate interfacial zones, micro cracks and porosity in aggregates. Although it is considered that because gel porosity resides in the hydration products that accumulate between the liquid phase and the anhydrous cement grains, gel porosity has major effect on hydration rates, the contribution of each remaining types of porosity should not be neglected. The results obtained with IPP and UPVT methods are confirmed with SEM images analysis: porosity is higher in the case of RC sample, although pores within SC sample are bigger. RC pores have spherical shape, unlike SC pores which are more irregularly shaped. Grains within RC are smaller and pores on aggregates are visible. Corundum grains are bigger in size: large corundum grains surrounded by cement matrix are visible in Figure 8.

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4. Conclusions

Conclusions are as follows:

1. The results presented in this paper contribute to the idea of including other testing methods in investigation of mechanical properties of concrete (i.e. nondestructive methods). Ultrasonic pulse velocity technique is rarely used in the high-temperature concrete investigation and has number of benefits because it is a nondestructive, simple, fast and reliable method. There is financial benefit in minimizing the number of samples for testing – saving in material and in time. 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.

2. Although recycled aggregate concrete showed lower compressive strength and higher porosity than commercial concrete it should be noted that both porosity and compressive strength are within satisfying value range for high-temperature application, i.e. these concretes will not be used as structural materials but as thermal insulation linings. In such application refractoriness is the property which is more important than strength. Considering the fact that compressive strength is above 50 MPa (and above 20 MPa at 1500 ºC) these concretes should be able to withstand load induced by other constructive parts of furnace and slag.

3. Refractoriness test showed that bauxite-based recycled concrete is highly resistible on increasing temperatures and creep test showed initiation of sintering process. Corundum concrete can be used for temperature above 1500 ºC.

4. Due to the satisfying performances it is concluded that recycled concrete can be equally used as standard concrete. Even though it has slightly lower properties, accent should be on the financial and ecological benefit found in using of recycled material and savings of energy and natural resources.

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