EFECTUL ÎNLOCUIRII AGREGATULUI CU GRANULE DIN CAUCIUC PROVENITE DIN ANVELOPE UZATE ASUPRA PROPRIETĂȚILOR MECANICE ALE BETONULUI

THE EFFECT OF THE AGGREGATE REPLACEMENT BY WASTE TYRE RUBBER CRUMBS ON THE MECHANICAL PROPERTIES OF CONCRETE

IONUȚ-OVIDIU TOMA, NICOLAE ȚĂRANU*, OANA-MIHAELA BANU, MIHAI BUDESCU, PETRU MIHAI, RAREŞ-GEORGE ȚĂRAN

[1]*Universitatea Tehnică "Gheorghe Asachi" din Iaşi, Str. Prof.dr.doc D. Mangeron, nr 67, Iaşi, 700050, România*

The growing amount of waste rubber produced from used tires has resulted in an environmental problem needed to be addressed. The paper investigates the effect of fine aggregate replacement by waste tyre rubber crumbs on the mechanical properties of concrete at different curing ages. The aim is to assess the suitability of the newly obtained material to load bearing elements in civil engineering.

The results presented in the paper are part of a larger research project related to the innovative use of all tyre components in concrete. The percentages considered were 40%, 60% and 80% by volume of fine aggregate. The general trend is a decreasing one in terms of mechanical properties. Even in such cases, the obtained values are above the minimum requirements, prescribed by norms, in terms of strength for some structural elements. The complete stress-strain curves determined at the age of 28 days show a softer descending trend for rubberized concrete compared to the reference mix. The embedded strain energy is larger in the post-peak region.

Cantitatea mereu crescândă de cauciuc provenit din anvelopele uzate a condus la o problemă de mediu care trebuie soluționată. În lucrare este investigat efectul înlocuirii părții fine a agregatului din beton prin granule din cauciuc asupra proprietăților mecanice a betonului la diferite vârste de întărire. Principalul scop constă în evaluarea oportunității noului material la realizarea elementelor portante din ingineria civilă.

Rezultatele expuse în lucrare reprezintă o parte din cadrul unui proiect de cercetare referitor la utilizarea inovatoare a componentelor anvelopelor uzate în elemente din beton. În lucrare se analizează influența înlocuirii părții fine de agregat cu granule din cauciuc în proporție de 40%, 60% şi 80% din volum. Tendința generală observată în cadrul programului experimental constă în descreşterea valorilor caracteristicilor mecanice. Totuşi, valorile obținute depăşesc cerințele minime prevăzute în norme pentru calculul de rezistență al elementelor structurale. Curbele caracteristice complete determinate la 28 de zile indică o descreştere atenuată în cazul betonului cauciucat comparative cu betonul obişnuit, iar energia potențială înglobată este mai mare pe porțiunea descendentă a diagramei tensiune-deformație specifică.

Keywords: *rubberized concrete, modulus of elasticity, compressive strength, complete stress-strain curve*

1. Introduction

The innovation in the construction industry is driven by both the need of reducing the environmental footprint [1, 2] and by the increasing demand of lowering the costs [3]. This can only be achieved by a constant and sustained innovation process which should also anticipate the future environmental constraints [4, 5].

The use of rubber crumbs obtained from recycled tyres could represent a significant resource for the construction industry, tremendously reducing its environmental footprint. Researchers realized the huge potential of the RC construction industry for embedding significant quantities of industrial wastes.

According to the latest report of European Tyre and Rubber Manufacturers Association [6], the European countries produced in 2013 roughly 4.67 million tonnes of tyres representing approximately 25% of the world production.

From these, an average of 58% reached their end of life. It is estimated that in 2012 alone, 2.765 million tonnes of used tyres were generated. During 2004 – 2012 the average rate of worn tyre recuperation was 89%. Over the last 19 years, the combination of material and energy recovery of ELTs (**E**nd of **L**ife **T**yre**s**) increased from 31% to 76% of total used tyres treatment while in the same time period landfilling decreased to only 6% (compared to nearly 50% in 1996). Out of the 1.05 million tonnes used for material or embedded

* Autor corespondent/*Corresponding author,*
E-mail: taranu@ce.tuiasi.ro

energy recovery, only a mere 11% is used in construction industry: sound insulation panels, slope stabilization, protection barriers and asphalts. The rest of 89% are used in product applications (running tracks, playgrounds, door mats, etc.).

From the first research works it was clear that replacing natural aggregates by rubber particles, even in small amounts, resulted in a sharp decrease of the compressive strength of concrete. Subsequent research [7] confirmed the earlier observations and demonstrated a decrease in the values of the static modulus of elasticity, as well [8]. Latest investigations on the influence of adding rubber on the durability of self-compacting concrete, the capability of rubberized concrete to dissipate energy [9], as well as determining the constitutive laws of rubberized concrete [10] are but a few of research directions in the field.

In Romania, the use of recovered materials from worn tyres in the forms of crumbs or powders in the construction industry is below 1% of the total mass. According to published statistics for the year 2013 [6], from the 33290 tonnes of recycled tyres only a small quantity, representing 6%, was used for obtaining rubber crumbs. The better part of it, 94%, was used as alternative fuel in cement kilns.

The paper presents some preliminary results on the effect of natural aggregate replacement by rubber crumbs obtained from waste tyres on the mechanical properties of concrete. The values of the static longitudinal modulus of elasticity in compression as well as the compressive strength of concrete were determined. The main parameters of the research were the replacement percentages by volume of the natural aggregates and the curing age of concrete. In addition, the complete stress-strain curve of concrete at the age of 28 days was determined following the procedure outlined in [10].

2. Materials and methods

2.1 Materials

A CEM I-42.5R type of cement readily available on the market was used. The rapid hardening cement was used in order to allow for the testing of concrete specimens at early ages. The river aggregates were with rounded edges to ensure that no concentration of stresses occurs.

The rubber crumbs, Figure 1, came from a local supplier. They were previously sorted according to their maximum grain size and cleaned from any impurities such as metal and textile parts that might have resulted from chopping and grinding the tyres.

Fig. 1- Rubber crumbs from worn tyres / *Granule din cauciuc din anvelope uzate.*

2.2 Methods

The mix proportions considered at this stage of the research are shown in Table 1. It has been adjusted so that a target compressive strength of at least 30 MPa would be obtained at the age of 28 days. A constant water to cement ratio of 0.47 was kept for all mix proportions.

The rubber crumbs replaced the fine aggregate (FA) in 40%, 60% and 80% by volume. In order to convert it to mass, the apparent density of rubber crumbs was determined. The obtained value of 506 kg/m3 is in line with the results reported in the specialised literature [8].

A number of 30 cylinders, 100 mm × 200 mm, was cast for each mix proportion shown in Table 1 for a total of 120 samples. The cylinders were demolded after 24 hours from casting and were kept in standard conditions, Figure 2, until the day of testing.

Fig. 2- Curing of concrete cylinders / *Maturarea epruvetelor ciclindrice.*

Table 1

Mix proportions / *Reţete de beton*

Mix designation	Cement (C) CEM I 42.5R	Water (W)	W/C	Aggregates			
				Sand	Rubber	Sort 4-8 mm	Sort 8-16 mm
	[kg/m^3]	[kg/m^3]	-	[kg/m^3]	[kg/m^3]	[kg/m^3]	[kg/m^3]
Ref	489	230	0.47	582	-	388	647
40%FA				532	50		
60%FA				514.8	67.2		
80%FA				492.4	89.6		

The density of the concrete specimens was assessed at 24 hours after casting. The cylinders were measured end weighed. A total number of 30 values were considered for the determination of the density of each concrete mix shown in Table 1.

Nine cylinders were used for the assessment of the static longitudinal modulus of elasticity in compression, as well as the compressive strength at the ages of 14, 21 and 28 days. The tests were conducted in accordance with SR EN 12390-13/2013 [11] and SR EN 12390-3/2009 [12], respectively.

The remaining concrete cylinders, three for each mix proportion, were used to determine the complete stress-strain curve following the procedure described in [10].

Given the number of specimens considered for each determination, a statistical analyses was run on the obtained results. The accuracy of the determinations was assessed by means of the coefficient of variation (COV). It is a standardized measure used in probability theory to express the dispersion of a probability distribution. The COV is expressed in percentage and it is calculated based on the following equation (1):

$$\mathrm{COV} = \frac{\sigma}{\mu} \qquad (1)$$

Where σ represents the Standard Deviation, equation (2), and μ is the average or mean value of the set of data, equation (3). The Standard Deviation is a statistical measure used to quantify the amount of variation or dispersion of a set of data values with respect to its average μ.

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(x_i - \mu\right)^2} \qquad (2)$$

$$\mu = \frac{1}{N}\sum_{i=1}^{N} x_i \qquad (3)$$

where N is the total number of data values and x_i represents the individual values in the entire set. Low values of Standard Deviation indicate that the data points tend to be close to the mean value of the set, also called expected value.

The complete stress-strain curve, at the age of 28 days, was obtained by closely following the procedure presented in [10]. Three cylinders were considered for each mix proportion shown in Table 1. The cylinders were machined to a flat surface using a specialized equipment to mitigate the friction between the cylinders and the loading plates of the universal testing machine, as much as possible.

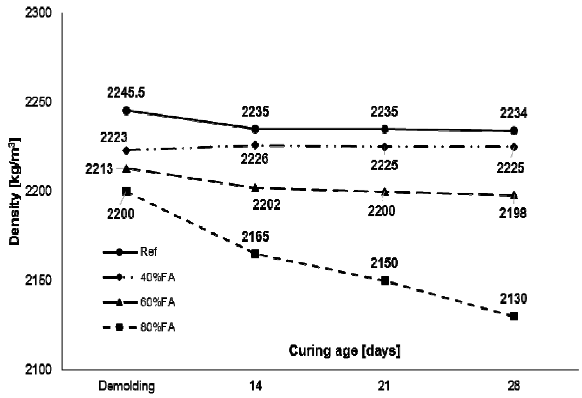

Fig. 3 - Change in density as function of the curing time / *Variația densității în funcție de vârsta de maturare a betonului.*

3. Results and discussions

3.1 Density

Figure 3 presents the variation of density with the age of concrete for each mix proportion considered in Table 1. In order to determine the density of concrete specimens, each cylinder was weighted and measured. Six values of the diameter and three for the height of each cylinder were measured. The average values were used to determine the volume of each concrete specimen. The density immediately after demolding was calculated as the average of 30 values.

A statistical analysis was applied for each set of measurements and the coefficient of variation (COV) was below 4%. This means a high accuracy of the results and ensures the repeatability of the data presented in the paper.

Although the general tendency is a decrease in the value of density with time, the difference is less than 1% between the values at 28 days and at 24 hours from casting.

Substituting the sand by rubber crumbs from worn tyres results in a small decrease in the values of the density. A 4.66% difference between the reference mix (Ref) and the 80%FA mix at the age of 28 days has been noticed. This can be explained by the fact that even though the replacement percentages are high, the values represent percentage by volume and not by mass. The corresponding mass percentages are much lower, as it can be seen in Table 1.

3.2 Compressive strength

The compressive strength (f_c) was determined at the ages of 14, 21 and 28 days, following the guidelines of SR EN 12390-3/2009 [12]. The uniaxial compression test was conducted on 9 specimens for each curing age at a constant loading rate of 0.6 MPa/s. Table 2 summarizes the obtained results for each mix proportion.

The obtained results were statistically processed in order to assess their accuracy. The computed coefficient of variation (COV) is also shown in Table 2. It can be observed that its

Table 2

Compressive strength of concrete at different curing ages
Rezistența la compresiune a betonului la vârste diferite

Mix designation	14 days		21 days		28 days	
	f_c [MPa]	COV [%]	f_c [MPa]	COV [%]	f_c [MPa]	COV [%]
Ref	32.77	3.52	33.47	3.11	35.56	2.87
40%FA	22.13	6.05	22.83	3.61	23.54	7.64
60%FA	20.23	5.92	21.58	3.51	23.08	6.96
80%FA	18.26	3.98	20.38	5.25	21.02	8.21

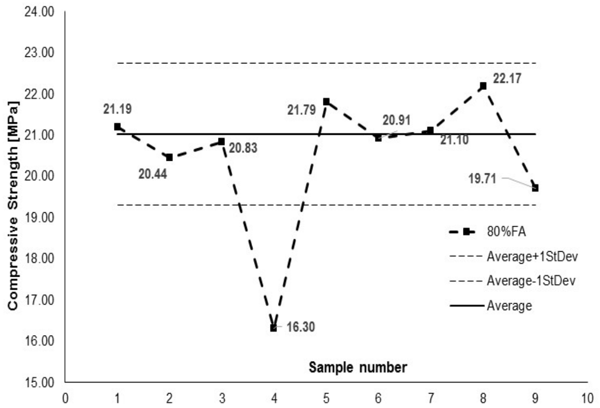

Fig. 4 - Statistical analysis for the compressive strength of 80%FA mix at 28 days / *Analiza statistică a valorilor rezistenței la compresiune pentru rețeta 80%FA la vârsta de 28 de zile.*

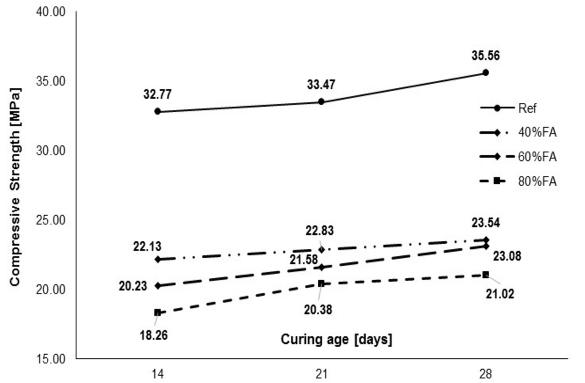

Fig. 5 - Variation of the compressive strength as function of the curing time / *Variația rezistenței la compresiune în funcție de vârsta de maturare a betonului.*

values are below the 10% limit generally considered to be the threshold below which the data is accurate. An illustration of the distribution of the results in terms of the compressive strength at the age of 28 days is presented in Figure 4 for the 80%FA mix.

Figure 5 shows the variation of the compressive strength over the considered time interval. The compressive strength of rubberized concrete decreases by 31% - 44% with respect to the reference mix. The higher the replacement percentage, the lower the compressive strength [8, 13]. It can be observed that the mixes 40%FA and 60%FA exhibit similar values for the compressive strength at the age of 28 days. From the perspective of sustainable development, the 60%FA mix is a better choice as it can use a larger quantity of rubber crumbs.

The behaviour of rubberized concrete in compression can be improved by means of confining, either externally or internally. The external confinement of regular concrete and reinforced concrete elements by means of composite fabrics proved to be very effective [14, 15]. The internal confinement can be achieved by using fibres made of different materials. This technique also showed improved results in terms of mechanical properties of concrete, as well as an improved behaviour of the reinforced concrete elements subjected to various types of loading conditions [16-18].

3.3 Longitudinal modulus of elasticity

The modulus of elasticity in compression was determined according to SR EN 12390-13/2013 [11]. The typical stress strain curve of concrete loaded in compression is shown in Figure 6. E1, E2 and E3, shown as thick lines in Figure 6, represent the slopes of the lines connecting the points of the nominal lower and upper stresses for the three consecutive loading cycles. These are, in fact, the values of the modulus of elasticity and they should not differ more than 10% between each other.

Nine cylinders were considered for each curing age of concrete. One of the nine specimens was tested in compression until failure in order to determine the compressive strength required to set the loading boundaries according to SR EN 12390-13/2013 [11] provisions.

The obtained values are shown in Figure 7. A similar tendency as with the compressive strength can be observed. The higher the replacement percentage, the lower the value of the modulus of elasticity in compression. However, the penalty is slightly lower, ranging between 22% - 32% depending on the percentage of rubber.

As with the compressive strength, the mixes 40%FA and 60%FA exhibit almost similar values of the modulus of elasticity at all considered ages of concrete with an average difference of 1.3%. The Young's modulus of 80%FA increases steadily closing the gap with respect to 40%FA mix

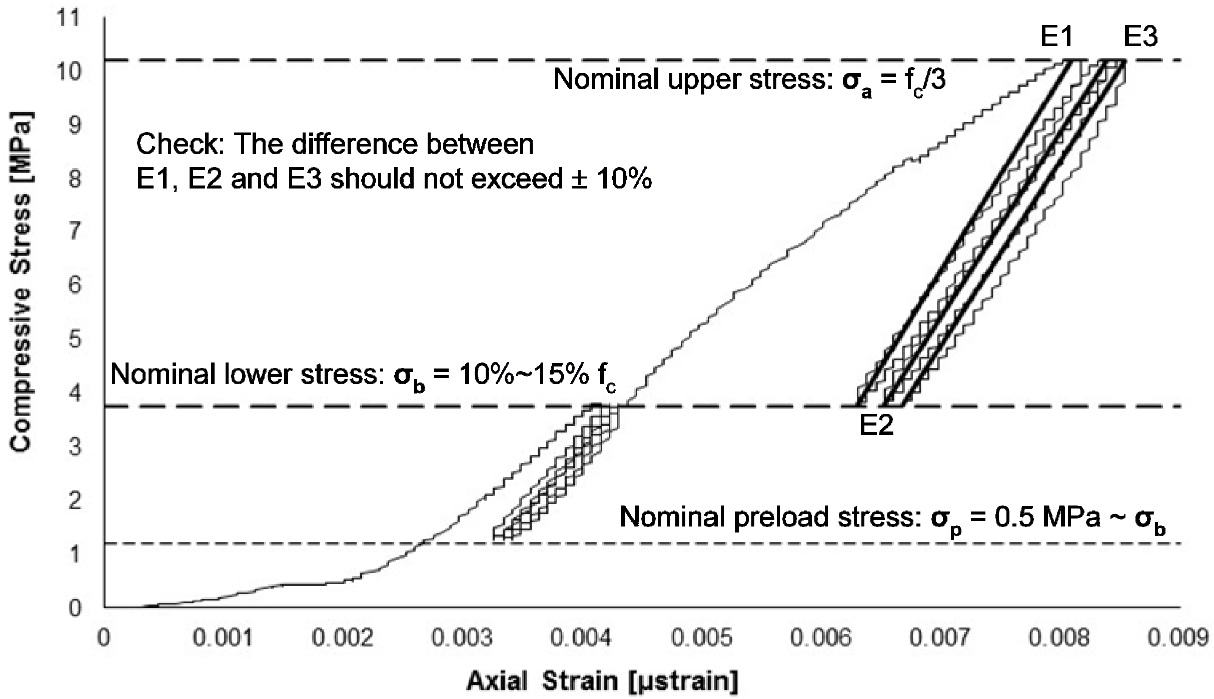

Fig. 6 - Typical stress-strain curve for the evaluation of the concrete modulus of elasticity in compression / *Curba tensiune – deformație specifică pentru evaluarea modulului de elasticitate la compresiune a betonului.*

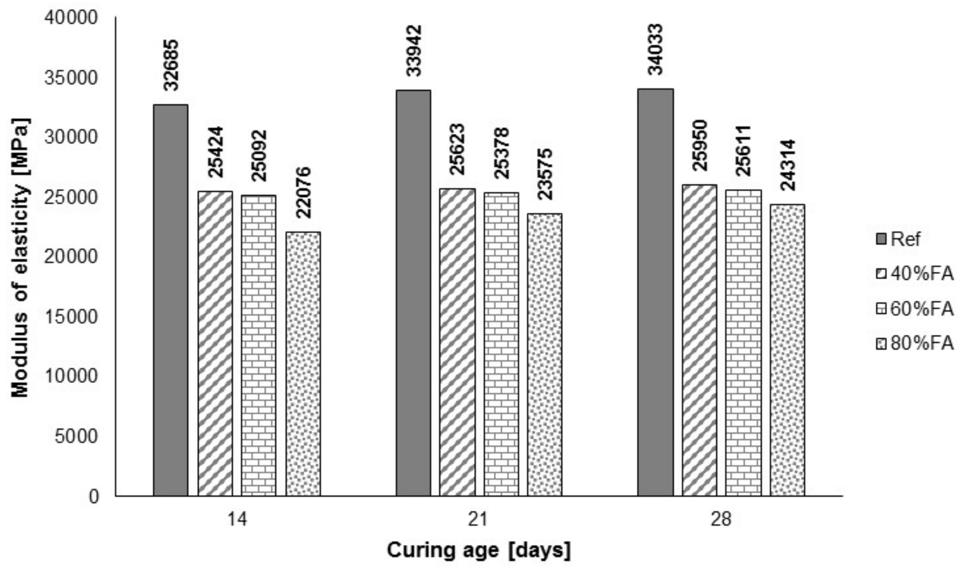

Fig. 7 - Modulus of elasticity at different curing ages / *Modulul de elasticitate la diferite vârste de maturare a betonului.*

from 13.17% at 14 days to only 6.3% at 28 days. On the other hand, the reference mix, the 40%FA mix and the 60%FA one, show small changes in the values of the modulus of elasticity of the considered time interval.

The results were compared to the data obtained from readily available empirical equations for assessing the modulus of elasticity based on the compressive strength of concrete and given in Eurocode 2 [19], ACI 363R-92 [20] and ACI 318M-05 [21] code specifications. Table 3 shows the obtained results by means of analytical solutions. From the presented data it can be concluded that the equation proposed in Eurocode 2 [19], overestimates the experimental results obtained on rubberized concrete by 7% - 20% depending on the rubber content and the age of the concrete. On the other hand, both ACI 363R-92 [20] and ACI 318M-05 [21] equations underestimate the experimental results obtained on rubberized

Table 3

The experimental values versus analytical ones for the modulus of elasticity
Comparație între valorile modulului de elasticitate al betonului obținute pe cale experimentală şi analitică

Mix designation	Experiment	Eurocode 2*		ACI 363R-92**		ACI 318M-05***	
		Calculated	Exp / EC2	Calculated	Exp/ACI363	Calculated	Exp/ACI318
	[MPa]	[MPa]	[%]	[MPa]	[%]	[MPa]	[%]
	14 days						
Ref	32685	31410	3.90	25905	20.74	26905	17.68
40%FA	25424	28174	-8.57	22758	12.30	22449	13.49
60%FA	25092	26906	-7.23	21585	13.98	20788	17.15
80%FA	22076	26342	-19.32	21076	4.53	20068	9.09
	21 days						
Ref	33942	31610	6.87	26107	23.08	27191	19.89
40%FA	25623	27915	-9.80	22514	11.44	22105	13.06
60%FA	25378	27623	-8.85	22243	12.35	21721	14.41
80%FA	23575	27428	-16.34	22062	6.41	21465	8.95
	28 days						
Ref	34033	32189	5.42	26698	21.55	28027	17.65
40%FA	25950	28426	-10.94	22996	10.25	22787	11.07
60%FA	25611	28060	-6.65	22651	13.91	26311	15.25
80%FA	24314	27536	-13.24	22163	8.85	21607	11.14

* $E_{cm} = 22 \times \left(\frac{f_{cm}}{10}\right)^{0.3}$ where $f_{cm} = f_{ck} + 8(MPa)$ [19]; ** $E_c = 3.32\sqrt{f_c^{'}} + 6.9$ where $f_c^{'}$ is the compressive strength in MPa [20]; *** $E_c = 4.7\sqrt{f_c^{'}}$ where $f_c^{'}$ is the compressive strength in MPa [21]

concrete by 4% - 14% and 9% - 17%, respectively. However, when it comes to the reference mix, all equations underestimate the experimental results; although the equation from Eurocode 2 [19] provides the closest values.

Therefore, it can be stated that the currently available empirical equations derived for the regular concrete should be cautiously used for rubberized concrete and new equations should be derived. For the time being, the amount of data is still insufficient for such an equation to be developed.

3.4 Complete stress-strain curve of regular and rubberized concrete

The complete stress-strain curve, at the age of 28 days, was obtained by closely following the procedure presented in [10]. Three cylinders were considered for each mix proportion shown in Table 1. The cylinders were machined to a flat surface using a specialized equipment to mitigate the friction between the cylinders and the loading plates of the universal testing machine, as much as possible.

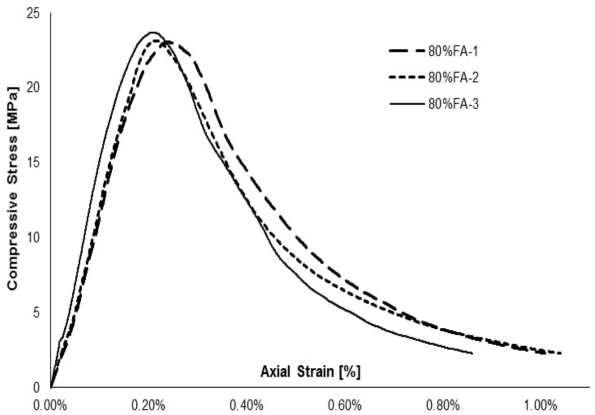

Fig. 8 - The complete stress-strain curves for the 80%FA mix individual samples loaded in compression / *Curba caracteristică completă pentru epruvetele cilindrice confecționate cu rețeta 80%FA.*

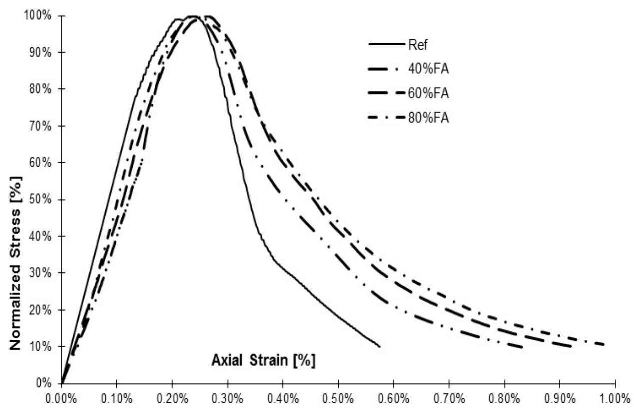

Fig. 9 - The normalized stress-strain averaged curves for the considered concrete mixes / *Curbele normalizate tensiune – deformație specifică obținute prin mediere pentru rețetele considerate.*

Table 4

The material characteristic values obtained from the complete stress-strain curves
Valorile caracteristicilor de material obținute de pe curba tensiune – deformație specifică

Mix designation	Peak stress, f_c	Strain corresponding to peak stress, ε_c	Strain energy	Pre-peak strain energy
	[MPa]	[‰]	[J]	[% of total]
Ref	36.26	2.62	223.22	41.35
40%FA	23.48	2.39	143.20	34.49
60%FA	22.53	2.55	163.26	36.46
80%FA	21.18	2.20	160.48	30.28

Figure 8 presents the complete stress-strain curves for the 3 samples considered for the 80%FA mix. Similar curves were obtained for the reference mix, the 40%FA mix and the 60%FA mix. The final stress-strain curves for each mix proportions were obtained by averaging the results. The final normalized stress-strain curves are shown in Figure 9 for all four mix proportions presented in Table 1. The data are summarized in Table 4 in terms of the average values for the peak stress, the corresponding peak strain and the stored strain energy.

It can be observed that increasing the rubber content in concrete results in a gradual decrease of the stress-strain curve in the post-peak region. This is of utmost importance since 60% of the strain energy of regular concrete is dissipated in the post-peak region. However, it can reach up to 70% in case of 80%FA mix.

4. Conclusions

Based on the obtained results it can be concluded that the general trend is a decreasing one in terms of mechanical properties of rubberized concrete by as much as 32% compared to the reference mix.

The compressive strength is highly influenced by the percentage of rubber crumbs substituting the sand in the mix proportion. The compressive strength of rubberized concrete decreases by 31% - 44% with respect to the reference mix depending on the replacement percentage and the curing age. The mixes 40%FA and 60%FA exhibit similar values for the compressive strength at the age of 28 days. From the perspective of the sustainable development, the 60%FA mix is a better choice as it can use a larger quantity of rubber crumbs.

The currently available empirical equations derived for regular concrete should be cautiously used for rubberized concrete. Therefore, new equations should be derived, but the amount of data is still insufficient for such equations to be developed.

The complete stress-stain curves determined at the age of 28 days show a softer descending trend for the rubberized concrete compared to the reference mix.

The stored strain energy is larger in the post-peak region and it can only be revealed when the complete stress-strain curve is plotted.

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MANIFESTĂRI ŞTIINȚIFICE / SCIENTIFIC EVENTS

Cementing the Future: The 1st International Conference on Grand Challenges in Construction Materials, Los Angeles, USA - From 17 March 2016 to 18 March 2016

Civil engineering infrastructure is aging and deteriorating, an issue, remediation of which involves huge maintenance and replacement costs. At the same time, due to the growth of the population/transportation, the need for infrastructure keeps increasing. These aspects need to be balances within the context of sustainability and reduction of CO_2 emissions allocated to the construction community.

The conference aims at identifying and discussing the “Grand Challenges” (of which there are many) in construction materials, and potential solutions to these. Focus is placed on identifying groupings of challenges, research directions for the academic community, and industry to undertake towards solution of such anticipated challenges.

Objectives

(1) To categorically elucidate present/emerging issues, limitations, and opportunities in construction materials.
(2) To emphasize how multi-scale (from atoms to continuum) experiments, modeling, and simulations can advance our understanding to take cement and concrete to the next level.
(3) To highlight the problems/solutions shared with other materials (e.g., glass, soft-matter), and how a multi-disciplinary approach, which blends best practices from different fields, can revolutionize concrete.

Sample Topics

(1) Ordinary portland cement based binders, including high-temperature processing, reactions with water, and additives for reaction/performance regulation, and composition-property relations,
(2) Alternative binders, that is, those based on alternate (non-portland) chemistries, composition-performance relationships, insights from composition-properties relations in modified silicate glasses,
(3) Control and evolution of microstructure in the context of setting, and mechanical properties, the role of additives, similarities with jamming/glass transitions.
(4) Structural evolution with time, loading, and moisture variations, which results in creep and shrinkage, its assessment and prediction. Such behavior shares similarities with aging in soft matter and glasses.
(5) Transport of moisture, ions, and steel corrosion dynamics. Special focus is placed on means for predictions, and corrosion inhibition.

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