ISSN 2066 – 8570 Volume **7**, Number **2**/**2015**

ASSESSMENT OF THE DYNAMIC PROPERTIES OF PLAIN AND RUBBERIZED CONCRETE

Ionuţ Ovidiu TOMA[1], Mihai BUDESCU[2],
Nicolae ŢĂRANU[3], Mihai Sergiu STRATULAT[4]

Rezumat. *Folosirea cauciucului obținut din anvelopele uzate ca resursă pentru industria construcțiilor poate conduce la o diminuare substanțială a impactului negativ asupra mediului. Determinarea caracteristicilor dinamice poate oferi informaţii importante legate de capacitatea de disipare a energiei a unui material. Acest lucru poate fi cuantificat prin fracţiunea din amortizarea critică şi a coeficientului de pierdere a unui material utilizat la structuri pentru construcții. Lucrare de faţă prezintă rezultate obținute în cadrul unui program experimental destinat determinării caracteristicilor dinamice pentru betonul clasic şi betonul cu adaos de granule din cauciuc provenite din reciclarea anvelopelor uzate. În lucrare se expun abordarea teoretică, metodologia experimentală cu detalii specifice studiului parametric realizat și rezultate obținute pe epruvete cilindrice.*

Abstract. *The use of rubber from discarded car tires as an alternative to natural aggregates in concrete may help preventing the complete depletion of natural resources and work towards a sustainable future. Moreover it can significantly reduce the environmental footprint of the construction industry. The assessment of the dynamic properties of a material are very important from the point of view of the energy dissipation capability of the investigated material. This can be determined from the dynamic modulus of elasticity, damping and the loss coefficients of the material. The paper presents the results obtained during an experimental program aimed at assessing the dynamic characteristics of plain and rubberized concrete containing rubber crumbs from discarded car tires. The theoretical background and the investigation methodology are presented with particular application to cylindrical concrete specimens.*

Keywords: dynamic modulus of elasticity, loss coefficient, rubberized concrete

---

[1]Senior Lecturer, PhD, The "Gheorghe Asachi" Technical University of Iasi, Faculty of Civil Engineering and Building Services, Department of Structural Mechanics, Iasi, Romania (iotoma@ce.tuiasi.ro)
[2]Prof., PhD, The "Gheorghe Asachi" Technical University of Iasi, Faculty of Civil Engineering and Building Services, Department of Structural Mechanics, Iasi, Romania (mbudescu@tuiasi.ro).
[3]Prof., PhD, The "Gheorghe Asachi" Technical University of Iasi, Faculty of Civil Engineering and Building Services, Department of Civil and Industrial Engineering, Iasi, Romania, full member of the Academy of Romanian Scientists (taranu@tuiasi.ro).
[4]Researcher, PhD, The "Gheorghe Asachi" Technical University of Iasi, Faculty of Civil Engineering and Building Services, Department of Structural Mechanics, Iasi, Romania (mihai.s.stratulat@gmail.com).

1. Introduction

Concrete is the most widely used construction material. In spite of minor and temporary setbacks, e.g. freezing and thawing resistance, alkali–silica reaction, concrete is still the material of choice when it comes to severe exposure conditions. Construction industry is the largest consumer of raw materials in the world with a yearly estimated quantity of 15 billion tones [1] and one of the largest environmental footprints [2]. Researchers and practitioners have realized the huge potential, especially of reinforced concrete constructions, for embedding significant quantities of industrial wastes [3].

Replacing natural aggregates by rubber particles, even in small amounts, resulted in a decrease of the compressive strength of concrete. Subsequent research [4] confirmed the earlier observations and demonstrated a decrease in the values of the static modulus of elasticity, as well [5].

Latest investigations on the influence of adding rubber on the durability of self-compacting concrete [6], the capability of rubberized concrete to dissipate energy [7] as well as determining the constitutive laws of rubberized concrete [8] are currently important research directions in the field.

The dynamic properties of concrete include the dynamic modulus, damping and loss coefficients. These are of importance in structural applications, particularly with respect to vibration control and noise reduction [9].

The dynamic modulus can provide valuable information to understand the dynamic response behavior of the material while damping is a material property characteristic of energy dissipation. It can be identified in the form of the decay of free vibration. Optimizing these dynamic properties can significantly improve structural reliability in terms of natural hazards and accidental loads such as explosive blasts and fragmentations [10].

In this paper, the preliminary results on the dynamic characteristics of plain and rubberized concrete are presented. The main parameter was the replacement percentage by volume of fine natural aggregates in concrete by rubber crumbs obtained from discarded tires. The considered replacement percentages were 40% and 60%.

2. Materials and methods

2.1. Materials

A CEM I-52.5R type of cement readily available on the market was used. The river aggregates were with rounded edges to ensure that no concentration of stresses occurs.

The rubber crumbs 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 tires.

2.2. Methods for the assessment of static properties of the material

The mix proportions considered at this stage of the research are shown in Table 1. The desired concrete strength class was C30/37.

A constant water to cement ratio of 0.28 was kept for all mix proportions. A high water reducing super-plasticizer, SIKA 20HE, was used in order to be able to obtain such a low water to cement ratio.

Table 1. Mix proportions

Mix designation	*Cement (C) CEM I-52.5R*	*Water (W)*	*W/C*	*Super plasticizer*	*Aggregates*			
					Sand	Sort 4-8	Rubber 4-8	Sort 8-16
	[kg/m^3]	[kg/m^3]	[%]	[kg/m^3]	[kg/m^3]	[kg/m^3]	[kg/m^3]	[kg/m^3]
Ref	330	92	28	1.98	856	293	0	797
SCA40						176	42.2	
SCA60						117	63.4	

The rubber crumbs replaced the small coarse aggregate (SCA) in 40% and 60% by volume. In order to convert it to mass, the apparent density of rubber crumbs was determined.

The obtained value of 506 kg/m^3 is in line with the results reported in the scientific literature [5].

A number of 30 cylinders, 100 mm × 200 mm, was cast for each mix proportion shown in Table 1 for a total of 90 samples. The cylinders were demolded after 24 hours from casting and were kept in standard conditions until the day of testing.

The cylinders were used for the assessment of the static longitudinal modulus of elasticity in compression at the age of 28 days. The tests were conducted in accordance with SR EN 12390-13/2013 [11].

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 [12].

2.3. Methods for the assessment of dynamic properties of the material

The dynamic modulus of elasticity of plain and rubberized concrete was determined in accordance to ASTM C215-08 [13] specifications. It is based on the Resonant Frequency Method and relies on the assessment of the fundamental longitudinal frequency of vibration.

Generally, damping is considered to be the property of a material or system to convert / dissipate energy under cyclic stress. Material damping is a name for the complex physical effects that convert kinetic and strain energy in a vibrating mechanical system consisting of a volume of solid matter into heat. The damping property of a material can be expressed either in terms of damping ratio, ζ, or in terms of loss coefficient, η.

The damping ratio may be determined either from the logarithmic decrement, equation 1, or in terms of the resonant frequency, as shown in equation 2. It is a measure of one very specific mechanism of damping, i.e., viscous damping which is proportional to velocity.

$$\zeta = \frac{\Delta}{\sqrt{4\pi^2 + \Delta^2}} \tag{1}$$

where:

$$\Delta = \ln\frac{x(t)}{x(t+T)} = \frac{1}{n}\ln\frac{x(t)}{x(t+nT)} \tag{2}$$

is the logarithmic decrement, $x(t)$ and $x(t+T)$ are the recorded consecutive amplitudes of the vibration, $x(t+nT)$ is the amplitude of vibration “n” cycles later from $x(t)$ and “n” is the number of cycles between the recordings.

$$\zeta = \frac{f_2 - f_1}{2f_n} \tag{3}$$

where f_n is the fundamental frequency of vibration and f_2 and f_1 are the half-power points corresponding to a 3dB decrease in the response resonant amplitude.

The higher the damping ratio, the larger the frequency range between the half power points. This second procedure has the advantage of requiring only steady-state tests.

As in the case of the free-decay procedure, associated with the assessment of the logarithmic decrement, only the relative amplitude of the response need be measured. However, the procedure does impose a particular stress history.

In case of impulse or shock loads the excitation force and the response function in terms of displacements cannot be written directly.

However, they can be described in terms of their Fourier transform as:

$$\bar{F}(\omega)=\int_{-\infty}^{\infty}F(t)e^{-j\omega t}dt$$
$$\bar{x}(\omega)=\frac{\bar{F}(\omega)}{k-m\omega^2+jk\eta} \tag{4}$$

where ω is the excitation frequency (Hz), m is the mass of the system (kg), k is the stiffness (N/m) and η is the loss coefficient.

The above equations contain both real and imaginary parts but knowing that $e^{j\omega t}=\cos(\omega t)+j\sin(\omega t)$ and if $k(\omega)=k(-\omega)$ and $\eta(-\omega)=-\eta(\omega)$ it follows:

$$x(t)=\frac{F_0}{\pi}\int_0^{\infty}\frac{(k-m\omega^2)\cos(\omega t)+k\eta\sin(\omega t)}{(k-m\omega^2)^2+(k\eta)^2}d\omega \tag{5}$$

where F_0 is the initial amplitude of the external force.

For k and η constant over all frequencies it results in $x(t)$ having finite values even for time steps less than 0, that is before any load is applied, which is physically impossible.

It follows that for real systems k and η cannot be constant over wide frequency ranges.

However, for very small values of η and for materials subjected to uniform stress distribution [14], a relatively accurate solution of the equation 5 is given in the form:

$$x(t)=\frac{F_0}{\sqrt{km}}e^{-\frac{1}{2}\eta t\omega}\sin(\omega t) \tag{6}$$

that is:

$$\Delta=\frac{\pi\eta}{2} \tag{7}$$

By comparing equation 7, in terms of the loss coefficient, with the equation of the logarithmic decrement in terms of damping ratio, equation 2, it follows:

$$\eta=2\zeta \tag{8}$$

3. Results and discussions

3.1. Static modulus of elasticity

Table 2 presents the results obtained for the static modulus of elasticity (E_s) for all mix proportions considered at this stage of the research. The COV is also shown for each calculated value of Young's modulus.

It can be observed that by replacing natural aggregates by rubber crumbs obtained from worn tires leads to a decrease in the value of modulus of elasticity. The higher the replacement percentage, the higher the decrease.

The results follow the general trend reported in the scientific literature [4, 5].

A 40% replacement, by volume, of small coarse aggregates results in a 6.67% decrease in the value of the static modulus of elasticity.

Increasing the replacement percentage to 60%, a 50% increase in replacement percentage, results in a 12.09% decrease for the modulus of elasticity, almost double compare to the previous case.

The small values of COV indicate a high accuracy and good traceability of the obtained results.

3.2. Dynamic modulus of elasticity

The dynamic modulus of elasticity was evaluated based on the following equation provided by ASTM C215-08 [13]:

$$\text{Dynamic}E\left(E_d\right) = DM\left(n'\right)^2 \tag{9}$$

where $n'$the fundamental longitudinal frequency (Hz), M is is the mass of the specimen (kg) and D is a coefficient depending on the shape and dimensions of the specimen.

For cylindrical specimens: $D = 5.093\frac{L}{d^2}$ where L is the length of the cylinder (0.2 m) and d is the diameter (0.1 m).

The obtained values of E_d for all considered mix proportions are shown in Table 2. It can be observed that E_d is greater than the static modulus of elasticity for both plain and rubberized concrete. The increase was 15% for the reference mix, 17% and 21% for the SCA40 and SCA60 mixes, respectively.

The values for the dynamic modulus of elasticity were obtained on two cylinders per mix proportion, each test resulting in very close values for the fundamental longitudinal frequency. Given the very small number of testes specimens, the COV was not computed for values of E_d.

Table 2. Static and dynamic modulus of elasticity

Mix designation	*Static Modulus of Elasticity, E_s**	*COV E_s*	*Dynamic Modulus of Elasticity, E_d***
	[MPa]	[%]	[MPa]
Ref	29518	2.51	33946
SCA40	27550	3.22	32234
SCA60	25950	3.68	31399

* Average value of 30 measurements
** Average value of 2 measurements

3.3. Damping ratio and loss coefficient

The loss coefficient η was computed based on the value of damping ratio ζ (equation 8). The latter was assessed by means of Resonant Frequency Method. The equipment used is shown in Figure 1. It consists of a vibration generator that sends the signal to a shaker. The latter transmits the vibrations to the concrete cylinder via a rod. Both the cylinder and the shaker have an accelerometer, Figure 1b; the former records the response of the concrete cylinder to the vibration motion induced by the shaker and the latter records the vibration of the shaker.

The recorded signal from the shaker is then compared to the output of the vibration generator and the controller makes the necessary corrections, Figure 1a.

Figure 2 presents the response of a plain concrete cylinder in frequency domain. Based on this graph, both the fundamental longitudinal frequency and the half-power points can be identified.

a) Controller and vibration generator.

b) Shaker with mounted accelerometer and cylindrical specimen.

Fig. 1. Equipment used to determine the dynamic properties of concrete.

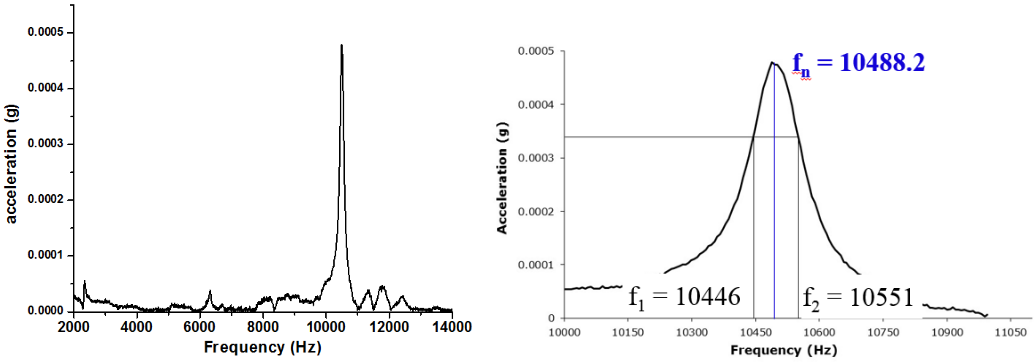

Fig. 2. Response of a plain concrete cylinder in the frequency domain.

The obtained results for all concrete mixes considered at this stage of the research are summarized in Table 3. The values of the damping ratio and loss coefficient are close to one another, despite the replacing of natural aggregates by rubber crumbs. This phenomenon can be explained by the fact that even though the replacement percentage is quite large, only one sort of aggregate is substituted by rubber. Therefore, when compared to the total volume of the aggregates, the replacement percentage is small.

Table 3. Damping ratio and loss coefficient

Mix designation	*Damping ratio,* ζ	*Loss coefficient,* η
	[%]	*[%]*
Ref	0.51	1.02
SCA40	0.516	1.032
SCA60	0.523	1.046

Conclusions

The paper presents the results obtained during an experimental program aimed at assessing the dynamic characteristics of plain and rubberized concrete containing rubber crumbs from discarded car tires. The theoretical background and the investigation methodology are presented with particular application to cylindrical concrete specimens. Based on the obtained results, the following conclusions can be drawn:

Substituting natural aggregates by rubber crumbs obtained from recycled vehicle tires leads to a decrease in the elastic properties of concrete. The higher the replacement percentage, the sharper the drop in the values of the static modulus of elasticity is observed.

A similar descending trend is observed for the dynamic modulus of elasticity. The latter is governed both by the fundamental longitudinal frequency of vibration and by the mass of the concrete cylinder. A decrease of about 500 Hz is observed in the fundamental frequency of vibration for cylinders made of rubberized concrete compared to the reference mix. Taking into account that these specimens are also lighter, smaller values of the dynamic modulus of elasticity are expected.

The general tendency reported in the scientific literature is also observed here: the value of the dynamic modulus of elasticity of either plain or rubberized concrete is greater than that of the static modulus by 15% ~ 21%.

The values of the damping coefficient and the loss factor increase slightly with the increase in rubber percentage. This is explained by the lower values for the resonant longitudinal frequencies of vibration for rubberized concrete specimens as well as by a wider bandwidth between the half power points.

Acknowledgment

This work was partially supported by the UEFISCDI project EU264/2014 – PN II/CAPACITATI.

R E F E R E N C E S

[1] I.O Toma, D. Covatariu, A.M. Toma, G. Ţăranu and M. Budescu, *Strength and elastic properties of mortars with various percentages of environmentally sustainable mineral binder*, Constr. Build. Mater., **43**, 348 (**2013**).

[2] G. Spaargaren and A.P.J. Mol, *Greening global consumption: redefining politics and authority*, Global Environ. Chang., **18**(3), 350 (**2008**).

[3] C. Meyer, *The greening of the concrete industry*, Cement Concrete Comp., **39**(8), 601 (**2009**).

[4] M.A. Aiello and F. Leuzzi, *Waste tyre rubberized concrete: properties at fresh and hardened state*, Waste Manage., **30**, 1696 (**2010**).

[5] A.O. Atahan and A.O. Yucel, *Crumb rubber in concrete: static and dynamic evaluation*, Constr. Build. Mater., **36**, 617 (**2012**).

[6] W.H. Yung, L.C. Yung and L.H. Hua, *A study of the durability properties of waste tire rubber applied to self compacting concrete*, Constr. Build. Mater., **41**, 665 (**2013**).

[7] J. Xue and M. Shinozuka, *Rubberized concrete: A green structural material with enhanced energy-dissipation capability*, Constr. Build. Mater., **42**, 196 (**2013**).

[8] L. Lijuan, R. Shenghua and Z. Lan, *Mechanical properties and constitutive equations of concrete containing a low volume of tire rubber particles*, Constr. Build. Mater., **70**, 291 (**2014**).

[9] K.B. Najim and M.R. Hall, *Mechanical and dynamic properties of self-compacting crumb rubber modified concrete*, Constr. Build. Mater., **27**, 521 (**2012**).

[10] M.M. Al-Tayeb, B.H. Abu Bakar, H. Ismail and H.M. Akil, *Effect of partial replacement of sand by recycled crumb rubber on the performance of hybrid rubberized-normal concrete under impact load: experiment and simulation*, J. Clean Prod., **59**, 284 (**2013**).

[11] SR EN 12390-13/2013, *Testing hardened concrete. Part 13: Determination of secant modulus of elasticity in compression*, Romanian Standard Association, (**2013**).

[12] I.O. Toma, N. Ţăranu, O.M. Banu, M. Budescu, P. Mihai and R.G. Ţăran, *The Effect of the Aggregate Replacement by Waste Tyre Rubber Crumbs on the Mechanical Properties of Concrete*, Rom. J. Mat. **45**, (in press) (**2015**).

[13] ASTM C215-08, *Standard test method for fundamental transverse, longitudinal and torsional resonant frequencies of concrete specimens*, ASTM International, (**2008**).

[14] D.I.G. Jones, *Chapter 37 – Applied Damping Treatments*, in C.M. Harris and A.C. Piersol (editors) – *Harris' Shock and Vibration Handbook, 5th edition*, McGraw-Hill, ISBN 0-07-137081-1, 1220 (**2002**).