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## DYNAMIC AND ENVIRONMENTAL ASSESSMENT OF SELF-COMPACTING CONCRETE

BY

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**Abstract.** Self-compacting concrete (SCC) has started to gain considerable interest in Europe due to its flowing characteristics under its own weight, which have an impact on speed, quality and cost of constructions (EFNARC, 2005). Determining the dynamic mechanical parameters such as elastic modulus and damping ratio is of great importance for both scientific material research and for the in-place assessment of buildings (IAEA, 2002). Having a new material in use, its behavior in measurement techniques established for other, similar, materials should be studied (RILEM, 2001). In this respect, we focused on evaluating the dynamic properties of SCC using the forced resonance technique and the impact method. The elastic modulus and the damping coefficient were calculated based on these measurements. Since the use of new materials has to be considered from an ecological point of view, simulations on the impact of this material on the environment have been made.

**Keywords:** self-compacting concrete; forced vibrations method; impact echo method; dynamic modulus of elasticity; material damping ratio.

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## 1. Introduction

Dynamic characterization is an important group of measurement techniques as they enable us to non-destructively obtain material parameters, either for laboratory specimens or for in-place structures. The elastic and rigidity modulus, Poisson's ratio and damping coefficient are amongst the most important of the parameters that can be dynamically determined. The main principle by which this is done implies finding out the resonance frequency and the width of the resonance peak. These can be obtained by means of several experiments (Malhotra and Sivasundaram, 2004), but two main types can be distinguished: forced resonance technique and impact method.

In the forced resonance technique, an induced signal of constant amplitude sweeps a certain frequency interval, while the response of the sample is recorded. The maximum response will take place for the natural frequency of the sample. The spectra can be obtained in different geometrical set-ups: longitudinal, transverse and torsional (Cores, 2003). Depending on which is performed, the value of the resonance can be used to calculate either Young's modulus (longitudinal and transverse) or the rigidity modulus (torsional).

On the other hand, the impact method relies on recording the response to a single hit. In this case, the signal contains, besides the frequency information, the decaying constant of a wave in the material. This can be used as an alternative for finding the damping coefficient (logarithmic decrement method). All geometries can be applied in this case also.

In this study we applied both methods to self-compacting concrete. The main focus was to determine to what degree measuring of these materials is accurately done with these methods and if there are discrepancies between them.

## 2. Experimental Methods

### Materials

- Cement – ordinary Portland cement CEM I 42.5 R, characterized by high level of early and final strengths.
- Aggregate - natural river sand as fine aggregates, river washed coarse aggregates with maximum size of 16 mm and a continuous gradation, specific gravity 2.7.
- Mineral admixture - local limestone filler with 2.6 specific gravity.
- Superplasticizer – was employed a polycarboxylates ether type HRWR, with a specific gravity of 1.04.

### Mix proportions

In order to investigate the dynamic properties of SCC were designed 3 mixes with different parameters. Cement content varied from 320 to 360 kg/m<sup>3</sup>, all mixtures were designed to have a constant w/b ratio of 0.53, paste volume

differed between 346-381 l/m<sup>3</sup>, sand content represented 48% of total aggregate content. The proportions of the produced mixtures are given in Table 1.

**Table 1**  
*Mix Proportions*

Mix designation	Cement (C) CEM I 42.5R	Water (W)	W/C	Limestone filler	Aggregates		
					Sand 0-4 mm	4-8 mm	8-16 mm
	[kg/m <sup>3</sup> ]	[kg/m <sup>3</sup> ]	-	[kg/m <sup>3</sup> ]	[kg/m <sup>3</sup> ]	[kg/m <sup>3</sup> ]	[kg/m <sup>3</sup> ]
SCC1	320	170	0.53	160	814	203	678
SCC2	340	180	0.53	150	809	202	674
SCC3	360	190	0.53	130	809	202	674

#### Mixing and casting details

The parameters such as mixer type, mixing sequence, etc. that can modify the properties of SCC during its production were kept constant.

The components were blended in a free fall concrete mixer. The cement, the aggregates and the limestone powder were efficiently mixed dry until attained an uniform distribution, sequential, 70% of water was added into the mixer and continued to blend. At last, the superplasticizers diluted with the remaining water was introduced and mixed to obtain a homogeneous mix.

The properties of fresh mixtures were evaluated according to EFNARC standards (EFNARC, 2005), the workability was determined by slump flow test, V-funnel and L-box test (Fig. 1). The results of testing are presented in Table 2. The concrete was placed in a steel cylinder (100 x 200 mm) without any vibration or compaction. After 24 h of casting, they were demoulded and stored in water for 28 days.



Fig. 1 – Testing SCC workability.

**Table 2**  
*Workability Tests Results*

Test	Slump flow, [mm]	T <sub>500</sub> , [s]	V-funnel, [s]	L-box
SCC1	680	4.2	14.4	0.84
SCC2	690	4.1	11.3	0.88
SCC3	720	2.9	9.2	0.93

### 3. Methods

**Forced Vibrations Method.** The dynamic properties of self-compacting concrete were measured by forced resonance in the 500-12000 Hz interval. The acceleration of the longitudinally induced signal was kept constant at 0.2 g and the frequency was increased with various rates for all samples: 0.5, 1, 2, 3, 4, 5, 6, 7, 8, 9 and 10 kHz per minute. The signal was generated by a control unit (VR9500 from Vibration Research) and transmitted to a high-frequency electro-mechanical shaker. On the shaker, a stinger was mounted to further induce the signal to the sample. Two types of measurements were done: with the stinger touching the sample (contact) and in close proximity without touching it (non-contact). We wanted thus to test if a contact interface between the stinger and the sample can induce noise or other adverse effects impairing the measurement. The obtained resonance peak can be further analyzed for a correct assessment of dynamic properties: frequency value is related to modulus of elasticity while its width is gives the material damping ratio.

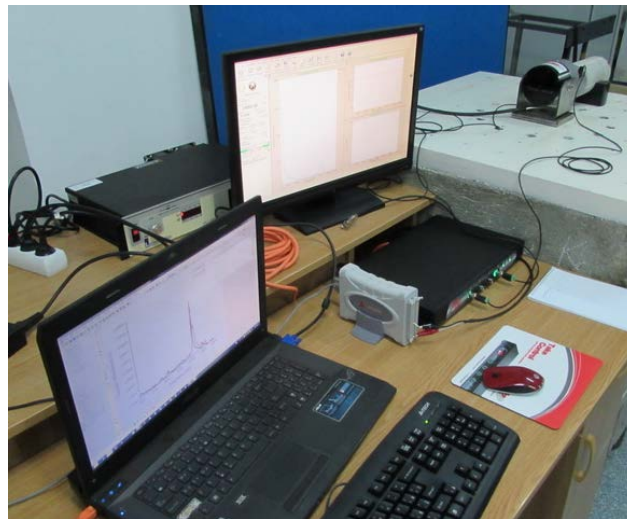


Fig. 2 – Experimental set-up for the assessment of dynamic material properties of concrete.

**Impact Resonance Method.** This method was used for all three geometrical cases (longitudinal, transversal and torsional). In order to establish the reliability of a quick assessment of dynamic parameters, the Fast Fourier Transform (FFT) was directly recorded, without interference in the actual signal of the accelerometer in choosing a correct interval.

**Dynamic Young's modulus.** The dynamic elastic modulus was computed using the values of the resonant frequencies as determined from the spectra obtained by both methods described earlier. Eqs. (1), (2) and (3) we used to relate the frequency, elastic modulus and size/shape characteristics, described in standardized test methods ASTM C215:

$$E_d = D \cdot m \cdot f_{ln}^2 \quad (1)$$

$$E_d = C \cdot m \cdot f_{tn}^2 \quad (2)$$

$$G_d = B \cdot m \cdot f_{rn}^2 \quad (3)$$

where  $E_d$  is the elastic modulus determined with the longitudinal natural frequency ( $f_{ln}$ ) in (1) and transversal natural frequency ( $f_{tn}$ ) in (2), and  $G$  is the rigidity modulus which is related to the torsional natural frequency ( $f_{rn}$ );  $D$ ,  $C$  and  $B$  are geometrical factors, and  $m$  is the weight of the sample.

The forced resonance was used only in longitudinal geometry due to experimental constraints, so only Eq. (4) was used in this case.

**Full Width at Half Maximum.** The damping ratio is computed by means of the following equation:

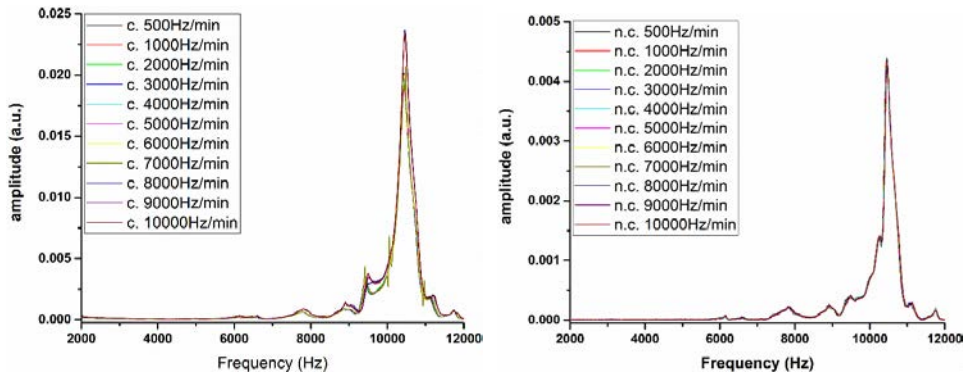
$$\zeta = \frac{1}{\sqrt{r^2 - 1}} \times \frac{f_2 - f_1}{2f_n} \quad (4)$$

where  $r$  is the ratio between the considered amplitude and the amplitude of the recorded signal at resonance. The method is based on the first resonant frequency of the sample  $f_n$  [Hz]. The considered  $f_1$  [Hz] and  $f_2$  [Hz] frequencies correspond to an amplitude equal to half the amplitude at resonance on both sides of the peak taken from the response spectrum.

#### 4. Results and Discussions

**Rate of Frequency Increase.** Forced resonance is standardized, but one parameter is not taken into consideration: the rate on increasing the frequency. Since the wave might suffer different processes inside the sample, at the interfaces between various constituents, we wanted to see if a regime closer to the steady state has an impact on the measurement.

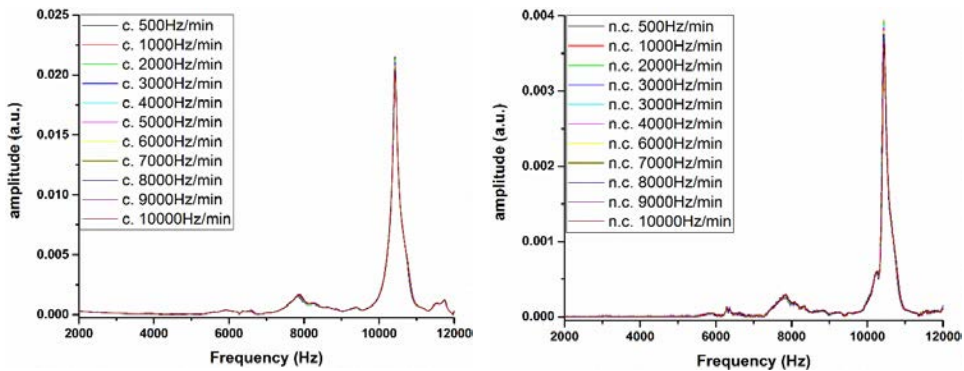
Increasing the frequency with different rates does not alter the measurements in a vital manner (Figs. 3, 4, 5), only a small shift to the right can be seen on both contacting and non-contacting experiments. Nevertheless, for the samples SCC1 and SCC3, it can be seen that higher rates can distort the measurements for contact forced resonance.



*a) Contact (c.)*

*b) Non-contact (n.c.)*

Fig. 3 – Response spectra of SCC1 concrete (Ref.) as function of frequency increase rate.



*a) Contact (c.)*

*b) Non-contact (n.c.)*

Fig. 4 – Response spectra of SCC2 concrete as function of frequency increase rate.

This can be seen in the zoomed in image around the resonance peaks presented in Fig. 6; from a certain frequency increase speed, especially for the SCC3 sample, the sample presents two peaks, probably because the material

does not uniformly transmit the vibration. As expected, the non-contact measurements have a lower amplitude than the contact ones, but little to no interference can be observed when higher increasing speeds are used.

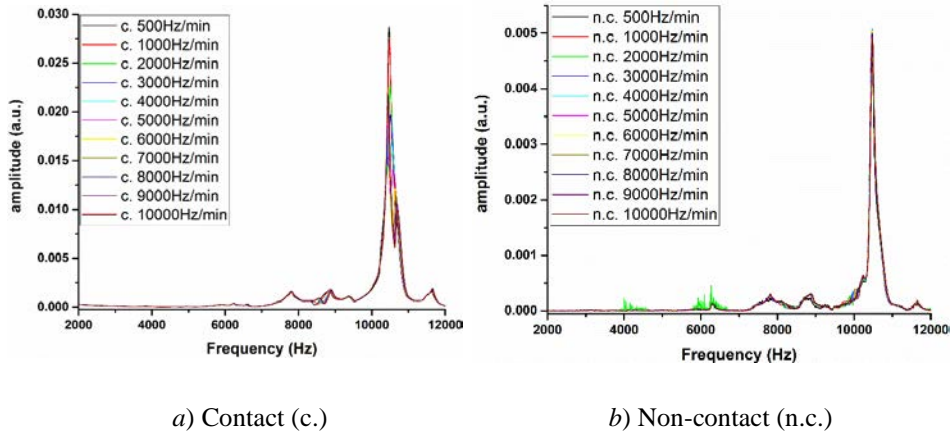


Fig. 5 – Response spectra of SCC3 concrete as function of frequency increase rate.

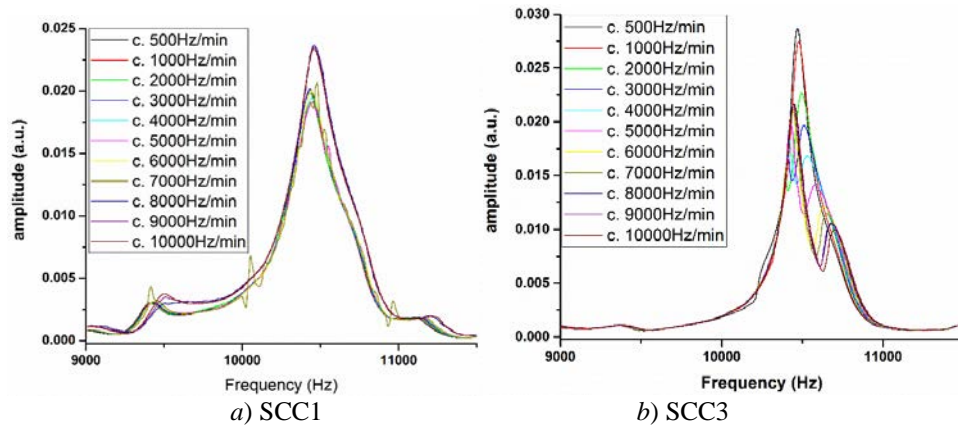


Fig. 6 – Response spectra of SCC3 concrete as function of frequency increase rate.

Peak fitting was performed on contact and non-contact measurements, only for the 1000 Hz/min tests, since lower rates do not influence SCC1 and SCC3. We obtained the values of the resonance frequency and the width of the peak, which are listed in Table 3. Using these values we calculated the dynamic Young’s modulus ( $E_d$ ) and the damping ratio ( $\zeta$ ), by means of Eq. (2) and Eq. (5) respectively.

$$\zeta = \frac{1}{\sqrt{r^2 - 1}} \frac{f_2 - f_1}{2f_n} \tag{5}$$

**Table 3**  
*Dynamic Parameters (Measured and Calculated) for All Samples*

Sample	Resonance frequency (Hz)		FWHM (Hz)		E <sub>d</sub> (GPa)		ζ (%)	
	<i>c.</i>	<i>n.c.</i>	<i>c.</i>	<i>n.c.</i>	<i>c.</i>	<i>n.c.</i>	<i>c.</i>	<i>n.c.</i>
SCC1	10451	10486	408	284	41.3	41.6	1.14	0.79
SCC2	10434	10458	193	172	41	41.2	0.5	0.48
SCC3	10494	10483	207	162	43.3	43.2	0.57	0.45

The results are consistent when compared between contact and non-contact, in both dynamic modulus and damping ratio. The only discrepancy appears for the sample SCC1, for which the damping ratio is influenced by the type of measurement, with higher damping in the case of the contacting experiment. This might be a measurement artifact, which can be improved upon, since no standardization exists for the non-contacting distance between the stinger and the sample, as there is no contacting pressure specified.

Various correlations have been proposed between the dynamic and static Young's modulus. We found the British standard to work best (BS 8110-part 2), which is an empirical equation:

$$E_s = 1.25 \cdot E_d - 19 \quad (6)$$

The results of the calculations and of static tests previously performed on samples of the same batch are presented in Table 4.

**Table 4**  
*Measured Static Values of the Elastic Modulus and Calculated Values Using the British Standard Correction*

Sample	Calculated static modulus (GPa)		Measured static modulus (GPa)
	<i>c.</i>	<i>n.c.</i>	
SCC1	32.6	33	31
SCC2	32.25	32.5	32
SCC3	35.1	35	33

**Impact Resonance Method.** The impact test was applied in all three geometries, for all samples. First, we plotted the longitudinal results against the previous forced resonance spectra (Fig. 7).



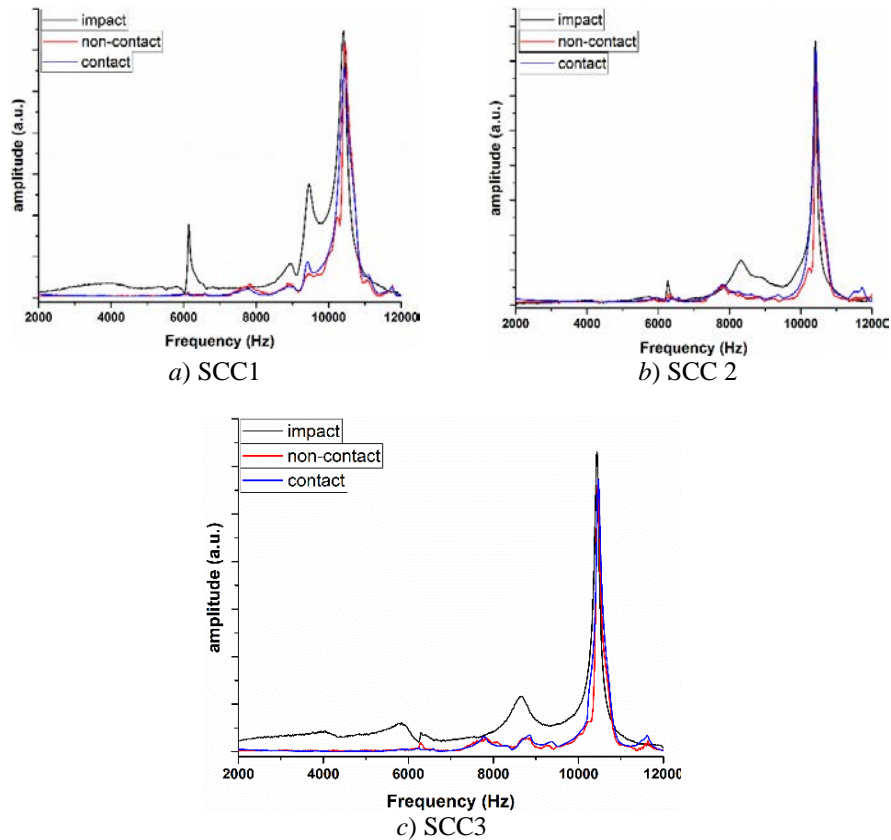


Fig. 7 – Comparison between longitudinal impact test the forced resonance method.

The results for the peak fitting procedures were used in the same way as for the previous test. Resonance values and peak widths are presented in Table 5, alongside the calculation results for Young's modulus and damping ratio.

**Table 5**  
*Longitudinal Impact Test Results*

Sample	Resonance frequency (Hz)	FWHM (Hz)	$E_d$ (GPa)	$\zeta$ (%)
SCC1	10387	319	40.8	0.89
SCC2	10397	146	40.6	0.41
SCC3	10426	164	42.7	0.45

The values of the impact method follow the same trend as the forced resonance test, with the mention that the non-contact type of experiment gives more similar results. We believe this to happen because the measurement is less impaired by possible unwanted effects that can appear at the stinger-sample interface.

Poisson's ratio is an important parameter that can be obtained through dynamic measurements, which can be mistakenly assumed as a certain value in further calculations for material characteristics (Popovics, 2008). It can be determined using the value of the dynamic Young's modulus (already calculated) and the dynamic rigidity modulus (Eq. (7)). The latter is computed from the torsional resonant frequency.

$$\mu = \frac{E}{2G} - 1 \quad (7)$$

In Fig. 8 the spectra of the obtained torsional impact experiments are presented for all three samples.

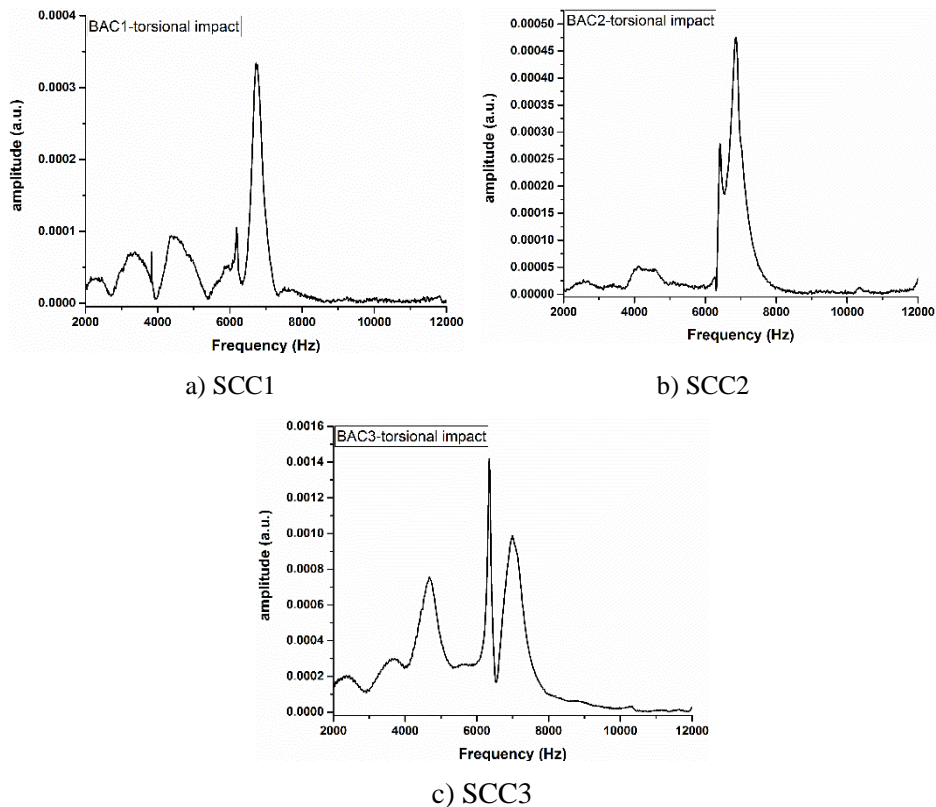


Fig. 8 – Torsional impact spectra for self-compacting concrete samples.

In the case of the SCC1 sample it is easy to distinguish the torsional response, but since the experiment is not easily done to include pure torsional signal, influences from the transversal transmission can appear. In the case of SCC2 and especially SCC3 this can be seen as secondary peaks that have to be

taken into consideration. In order to properly assess the value of the torsional resonant frequency, we thus performed transversal tests, so that we could pinpoint the location of this frequency (Fig. 9).

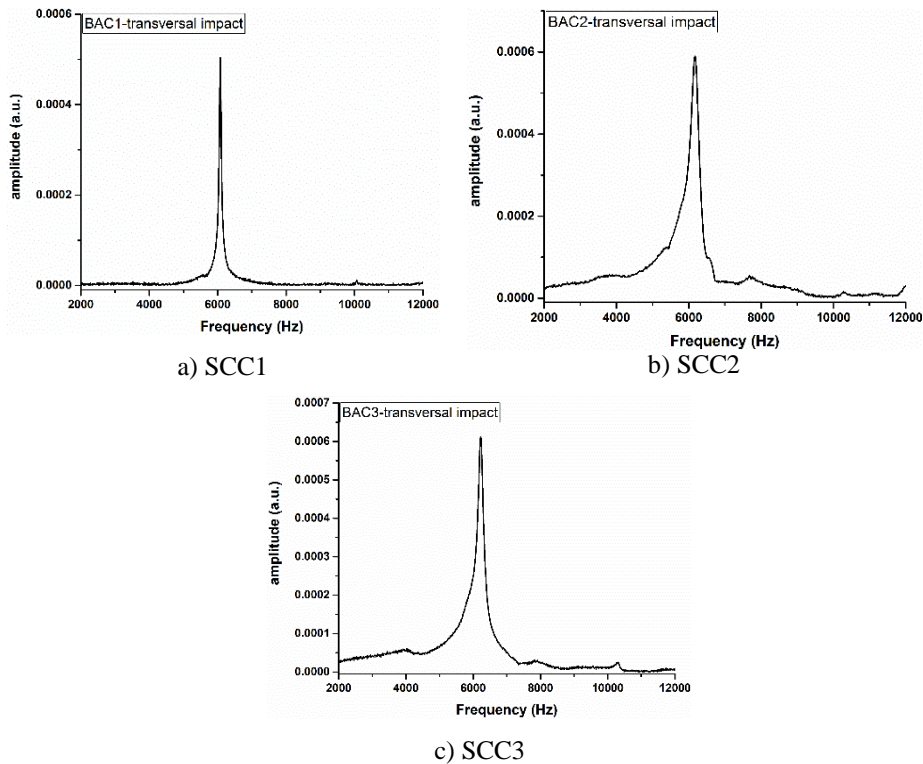


Fig. 9 – Transversal impact spectra for self-compacting concrete samples.

The transversal response is very sharp, with no other influences, so this frequency can be easily determined and subtracted from the torsional experiments. Thus we found out the torsional resonant frequencies and used them to compute the dynamic Poisson's ratios for all three samples, using also the dynamic Young's modulus determined beforehand (Table 6).

**Table 6**  
*Torsional Impact Test Results, with Calculated Values of Rigidity Modulus (G) and Poisson's Ratio ( $\mu$ )*

Sample	Resonance frequency, (Hz)	G, (GPa)	$\mu$
SCC1	6758	17	0.18
SCC2	6856	17.6	0.14
SCC3	6995	19.6	0.1

## 5. Conclusions

Dynamic tests have been successfully performed on three self-compacting concrete recipes. Both impact resonance and forced oscillations tests were employed.

The results show that Young's modulus does not present a clear linear variation with the cement content. It is highest for the highest quantity of cement used in the recipe (SCC3). The values for SCC1 and SCC2 are somewhat similar and lower than for SCC3, but a trend can be inferred, which is the opposite: decreasing of the dynamic modulus with increasing cement quantity.

Results for damping capabilities of the material, for both the impact test and the forced oscillations, show a sharp decrease when increasing the cement content over the quantity used in SCC1 (which shows the biggest value of the damping coefficient).

The dynamic modulus has been successfully correlated with the static elastic modulus through the empirical equation proposed by the British standard. Thus, it can be concluded that the non-destructive dynamic tests can be used with viable results for self-compacting concrete.

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## DETERMINAREA CARACTERISTICILOR DINAMICE ALE BETONULUI AUTOCOMPACTANT

(Rezumat)

Interesul considerabil manifestat față de betonul autocompactant se datorează abilității sale de curgere sub influența greutatei proprii, contribuind astfel la creșterea calității elementelor, sporirea vitezei de lucru și reducerea costurilor de execuție a

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construcțiilor. Modulul de elasticitate și coeficientul de amortizare prezintă parametri dinamici importanți atât pentru cercetarea științifică cât și pentru evaluarea în situ a construcțiilor. Deoarece BAC prezintă un material relativ nou, este necesară evaluarea proprietăților dinamice ale acestuia. În acest sens, în cadrul acestui studiu, au fost utilizate două metode de determinare: metoda fenomenului de rezonanță și metoda de impact. Metoda de rezonanță presupune inducerea unui semnal de amplitudine constantă, într-un anumit interval de frecvență, unei probe de beton și înregistrarea răspunsului, acesta având valori maxime pentru frecvența reală a materialului. Metoda de impact se bazează pe înscrierea răspunsului la aplicarea unei singure forțe, de o valoare mică. În acest caz, semnalul conține suplimentar informațiilor de frecvență, date informaționale necesare determinării coeficientului de amortizare.

