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CORRELATION BETWEEN DYNAMIC MODULUS OF ELASTICITY AND COMPRESSIVE STRENGTH FOR SELF-COMPACTING MORTARS

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Abstract:

Application of non-destructive testing methods in defining the mechanical properties of mortar and concrete is continually developing. Self-compacting or self-leveling mortars are already widely applied in construction of new structures. As self-compacting mortars are finding their place in rehabilitation and repair of reinforced concrete structures, it is of high importance to design mixtures with compressive strength and modulus of elasticity compatible with existing concrete. Ten mortar series with variation of component materials (fly ash, recycled concrete aggregate, crushed brick aggregate and crushed brick filler) were the subject of following tests: resonant frequency, ultrasonic pulse velocity and compressive strength of mortar. Dynamic modulus of elasticity was calculated using the first two methods mentioned. Results from resonant frequency measurements were then used for calculating compressive strength of the mixtures through different models developed for ordinary concrete and available in the literature. It was shown that the model proposed by Gardner is closest to describing the behavior of mixtures with different component materials, but would need some corrections in order to be used for these purposes.

Key words: dynamic modulus of elasticity, resonant frequency, ultrasonic pulse velocity, self-compacting mortars

1. Introduction

Development of concrete and mortar testing methods is headed towards advances in non-destructive and non-invasive testing (NDT) methods capable of indicating mechanical, acoustical, chemical, electrical, magnetic and physical properties of materials [1]. Special attention has been devoted to acoustic techniques. NDT techniques are quite sensitive to physical properties and provide only an indirect way towards material mechanical performances. The main causes of uncertainties of NDT methods are that factors other than one we are trying to determine may influence the NDT measurement result and cause the variability of NDT measurements [2].

Two properties often evaluated through NDT techniques are compressive strength and modulus of elasticity of concrete or mortar. Both of these properties are very important for designing and analyzing the strength and serviceability of concrete structures [3], and deciding on the material suitable for repair of an existing concrete structure. Methods used to determine dynamic modulus of elasticity are commonly based on measuring longitudinal frequency or ultrasonic pulse velocity (UPV). The measurements are based on the fact that the natural frequency of a vibrating structural member is a function of its dimensions, dynamic modulus of elasticity and density. It has been shown that the values of dynamic modulus of elasticity may vary, depending on method of measurement used. It was noticed in previous studies that higher values are obtained through the UPV measurements [4]. These differences increase with increased level of porosity in brittle materials [5].

The fundamental resonant frequencies are determined using one of two alternative procedures: the force resonance method or the impact resonance method, and measurements can be conducted in longitudinal, transversal and torsional direction [6].

In the ultrasonic pulse velocity method, an ultrasonic wave pulse through concrete is created at a point on the surface of the test object, and the time of its travel from that point to another is measured. It is established that the velocity of a pulse of compressional waves through a medium depends on its elastic properties and density [7]. Other factors that can influence the measured values of the UPV are aggregate content in composite, maximum grain size, type (density) of the aggregate, content and type of cement paste, water/cement ratio, etc. Size and shape of specimen usually do not affect UPV values, but relation between these values and dynamic modulus of elasticity is valid only in the case when the smallest lateral dimension of the specimen is greater than the wavelength of the pulse [2].

Since, it is impossible to measure values of static modulus of elasticity directly, once the concrete is placed in the structure, determining the correlation between values of static and dynamic modulus of elasticity is important. Many attempts have been made to achieve this during the years. It was shown that values of dynamic modulus are usually higher than static modulus due to the heterogeneity of the concrete composition. In the most cases formed correlation was linear function (Lydon and Balendran, Swamy and Bandyopadhyay, Shkolnik) [4].

Self-compacting mortar, investigated in this paper, by definition, need to be placed into formwork without vibrating or any additional actions. Although, they are usually considered as a step in design of self-compacting concrete, recently they have been applied in the rehabilitation and repair of reinforced concrete structures [8]. Apart from their good properties in fresh state, necessary for adequate placement on the damaged concrete elements, self-compacting repair mortars have to achieve equal or improved mechanical properties compared to the concrete in question. Compatibility between compressive strength and modulus of elasticity between repair mortars and original concrete is therefore of great importance.

Carrasco et al. investigated possibilities of application of the iron-ore tailings as aggregate replacement in renders, through measurements of static and dynamic modulus of elasticity. It was concluded that correlation between two modulus of elasticity for different mixtures was linear function, dependent on the amount and type of aggregate used [9].

Dynamic modulus of elasticity (determined through measurement of resonant frequency in longitudinal direction and UPV methods) and compressive strength of different self-compacting mortar (SCM) mixtures are presented in this paper. Measured values of compressive strength were than compared with the different values calculated through theoretical models that can be found in literature and correlate compressive strength with modulus of elasticity of concrete mixtures.

2. Materials and mixtures

Ten series of SCM were designed incorporating by-products (fly ash) and recycled materials (crushed brick and recycled concrete aggregate).

These materials were used in two different ways. One (regarding filler) was partial replacement of limestone filler (LF) with fly ash (FA) or crushed brick powder (CBP), and the second one (regarding aggregate) was partial replacement of river aggregate (RA) with crushed brick (CB) or recycled concrete aggregate (RCA). Basic properties of the component materials are presented in Table 1.

The same ratios between the solid components (m_c:m_f:m_a=1:1:3.375), were adopted for all of the tested mixtures, m_c –mass of cement, m_f – mass of mineral filler and m_a – mass of aggregate. Mass of water for the series varied, due to targeted similar properties of fresh mortar (200 – 300 mm slump flow diameter, as shown in Figure 1), while the amount of superplasticizer was the same for all of the mixtures (1.5% m_c) [10]. Series design and properties are presented in Table 2. Series R1 and R2 represent referent mixtures with limestone filler used as mineral filler and river sand used as aggregate. Difference between these two mixtures was in type of cement used.

Material	Type	Specific density (kg/m^3)	Average diameter (µm)
Cement	CEM II/A-M (S-L) 42.5R	3040	<63
Cement	CEM III/B 32.5 N SR-LH	3150	<63
Limestone filler	Pescar, Ljig	2720	250
Fly ash FA	Kostolac	2210	<63
Crushed brick powder CBP		2400	<63
River aggregate	River Danube origin	2640	90-2000
Crushed brick aggregate CB		2400	90-500
Recycled concrete aggregate RCA		2500	90-500
Superplasticizer	Adium 132	1030	-

Table 1. Properties of the component materials

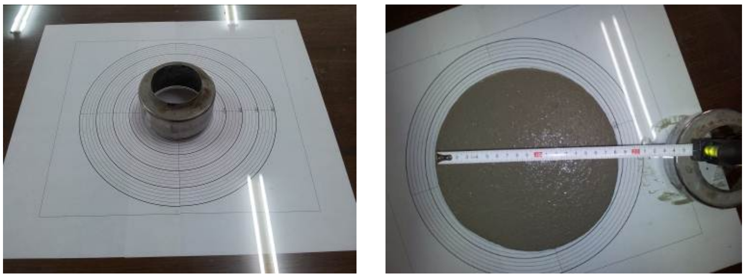

Figure 1. Slump flow test

Mixture	Type of cement	Type of mineral filler	Type of aggregate		Water/cement ratio	Content of the aggregate (%)
			0.09/0.5 mm	0.5/2.0 mm		
R1		LF	RA	RA	0.751	55.0
F1		LF+FA	RA	RA	0.822	54.3
FCB		LF+FA	CB	RA	1.167	53.0
FRCA	CEM II/A-M (S-L) 42.5R	LF+FA	RCA	RA	1.023	54.2
C1		LF+CBP	RA	RA	0.747	55.0
CCB		LF+CBP	CB	RA	1.132	51.8
CRCA		LF+CBP	RCA	RA	0.974	54.7
R2		LF	RA	RA	0.750	54.7
F2	CEM III/B 32.5 N SR-LH	LF+FA	RA	RA	0.820	54.3
C2		LF+CBP	RA	RA	0.748	55.1

Table 2. Series mix design

Series F1 and F2 contained both limestone filler and fly ash, while series C1 and C2 contained crushed brick powder as partial mineral filler replacement of limestone powder (in amount of 50%). Finally, series FCB and CCB, apart from mineral filler replacement, had aggregate 0.09/0.5 mm replaced with crushed brick of the same grain size (0.09/0.125 mm, 0.125/0.25 mm and 0.25/0.5 mm). The same procedure was repeated for series FRCA and

CRCA, both made with recycled concrete aggregate. Series F2, and C2 are equivalents to the series with index 1, only difference being type of cement used in these mixtures.

Fresh mortar was poured into the standard prismatic molds (4×4×16 cm) without vibration or any other additional actions, and then cured under wet covers during the first 24 hours. After demolding, samples were cured under water until testing.

3. Analysis and results

Ultrasonic pulse velocity, resonant frequency and mass were measured on standard mortar specimens (4×4×16 cm). Samples were tested after one hour of drying in laboratory conditions. Measurements were conducted on three samples for each series, after 1, 3, 7, 28 and 56 days. The second group of samples was exposed to the compressive strength testing at the same ages.

Measured values were used for calculation of dynamic modulus of elasticity. Using resonant frequency, dynamic modulus of elasticity can be calculated as [11]:

$$E_d = 4.079 \cdot 10^{-5} \cdot \frac{m \cdot l}{d^2} \cdot f^2 \tag{1}$$

On the other hand, using ultrasonic pulse velocity, dynamic modulus of elasticity can be calculated as [12]:

$$E_d = v^2 \cdot \gamma \cdot \frac{(1+\mu)\cdot(1-2\cdot\mu)}{(1-\mu)}. \tag{2}$$

In equations (1) and (2) m represents mass of the sample in kg, l – length of the sample in cm, d – height of the prism, f – resonant frequency, v – ultrasonic pulse velocity in m/s, γ – bulk density and μ – dynamic Poisson's ratio (adopted value 0.2). It was shown, as stated before, that calculated values of dynamic modulus were 1.7- 9.6% higher when calculated using equation (2), with exception of series R2. Calculated moduli of elasticity at the age of 28 days are presented in Figure 2 for all mixtures.

Influence of the grain size on differences between the mixtures was eliminated by using the same grain size distribution in all of the series. Series with partial replacement of mineral filler showed small differences in measured values when compared to referent mixtures (less than 5% for series F1 and C1 compared with R1; less than 10% for series F2 and C2 compared with R2). Differences between measured values of modulus of elasticity for other series confirm conclusions form literature that modulus of elasticity of concrete depends on the values of modulus of elasticity of paste and of aggregates [13].

Similar behavior was noticed regarding measured compressive strength values. Figure 3 presents compressive strength values at the ages of 28 and 56 days. Series made with fly ash and cement 42.5 R show higher strength values, especially after 56 days when compared to the referent mixture (R1) and mixtures with crushed brick powder. Series made with cement 32.5 N, showed very small differences of compressive strength after 28 and 56 days (less than 0.3% for 28^{th} day strength and less than 2.2% for 56^{th} day strength).

When measured values of dynamic modulus of elasticity, calculated through resonant frequency method, and compressive strength were plotted on the same diagram separately for each series, exponential correlation (eq. 3) with high value of correlation coefficient (lowest value equaled 0.9826) was developed for each of the series.

$$f_c = A_1 \cdot e^{A_2 \cdot E_D} \tag{3}$$

It was shown that this correlation, more precisely coefficient A_2 depended mostly on the bulk density of the mixture and, indirectly, type of component material used, as shown in Figure 4. Carrasco et al. also showed that percent of aggregate replacement and grain size of aggregate used affected the correlation between values of compressive strength and modulus of elasticity of mortars [9].

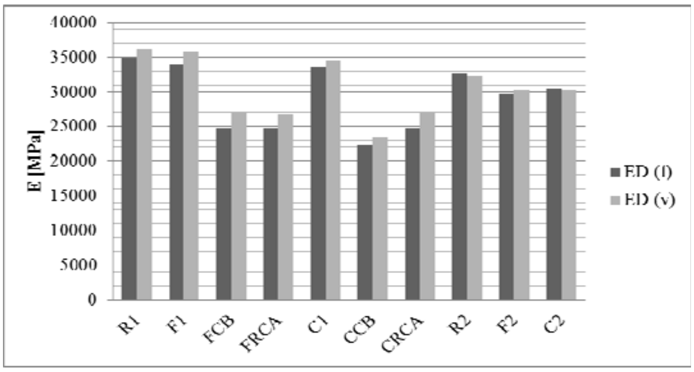

Figure 2. Dynamic moduli of elasticity after 28 days calculated from resonant frequency method and UPV method

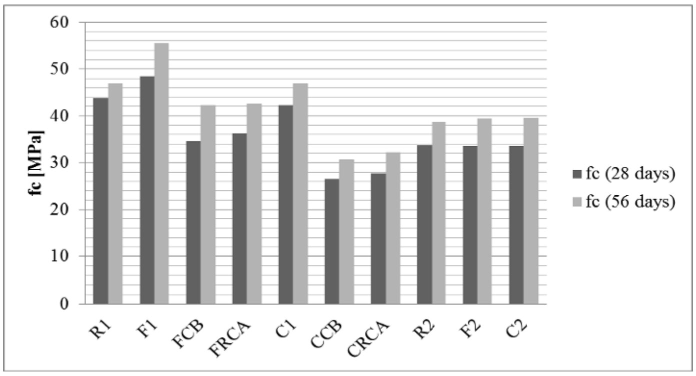

Figure 3. Compressive strength at the age of 28 and 56 days

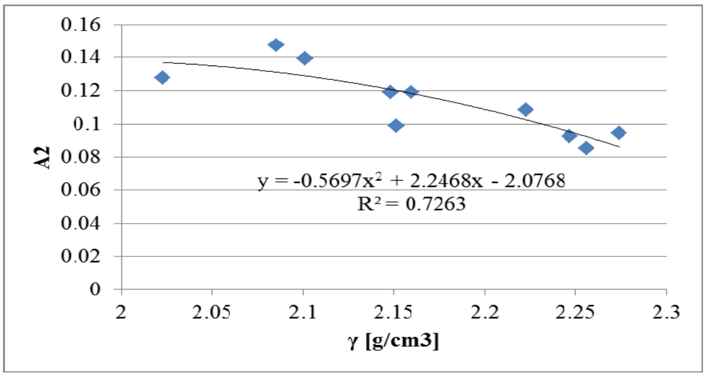

Figure 4. Dependency of the coefficient A2 on the bulk density γ

Measured compressive strength values were also compared with the values calculated using prediction equations that can be found in the literature [14], and connect modulus of elasticity and compressive strength of normal concrete.

CEB-FIB-99/Eurocode 2 (EC 2),
$$f_c' = \left(\frac{E_c}{21500}\right)^{3/2} \cdot 10 \quad (4)$$

Gardner (G)
$$f_c' = \left(\frac{E_c - 3500}{4300}\right)^{2} \quad [15] \quad (5)$$

Serbian concrete regulations – (BAB'87),
$$f_c' = \left(\frac{E_c}{9.25}\right)^{3} - 10 \quad (6)$$

In these formulas E_c represents elastic modulus of elasticity and f_c' compressive strength of the concrete.

The correlation between the static and dynamic moduli is considered to be unaffected by the air entrainment, method of curing, ambient conditions at test or the type of cement used [16]. Conducted studies show that, although the dynamic modulus of elasticity of concrete has higher values than static modulus, there is a linear correlation between these two parameters [4,9]. For this reason mentioned models were used in this paper for predicting compressive strength of material whose dynamic modulus of elasticity is known. Calculated and measured values of compressive strength for referent series and series with partial replacement of the filler are presented in Figure 5, while values for series containing partial replacement of aggregate are presented in Figure 6. Development of strength through time is presented in logarithmic scale, while $f_{c,\,av}$ presents average measured value of compressive strength.

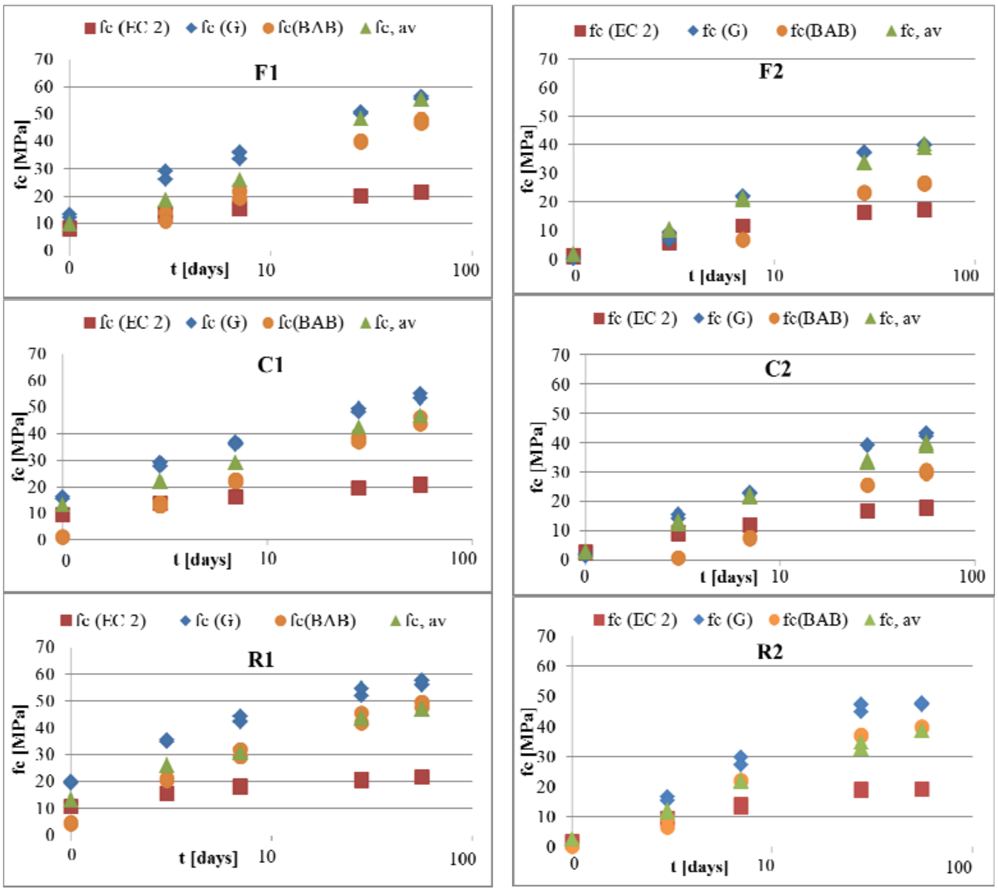

Figure 5. Measured and calculated compressive strength of the series R1, R2, F1, F2, C1 and C2

Model proposed in EC 2 underestimated the compressive strength of all mortar series (for more than 50%). Model proposed in BAB'87 was suitable for calculation of compressive strength of referent mixtures at the age of 28 and 56 days (differences smaller than 10%), but underestimated values for all other mixtures. On the contrary, model proposed by Gardner showed sensitivity to composition of self-compacting mortar mixtures. Compressive strength values calculated in this way overestimated measured values for referent mixtures and mixtures with partial replacement of mineral filler, but underestimated values measured on mixtures with partial replacement of aggregate. For series R1, R2, C1 and C2 improvements in modeling are achieved by calculating static moduli of elasticity as 0.85-0.95 E_D (differences in percent drop from 40% to less than 10%). Application of models correlating static and dynamic modulus of elasticity suggested by Lydon and Balendran, Swamy and Bandyopadhyay, Shkolnik and Popovics gave values of compressive strength that greatly underestimated measured values.

Differences are smaller for mixtures F1 and F2 that, due to pozzolanic reactivity of fly ash, reach higher compressive strengths in older ages (for higher values of compressive strengths differences were lower than 10%). For mixtures FCB and FRCA differences between values calculated through Gardner's model and measured values were small for early age strengths (less than 1% and 15% respectively) but increased for older samples and reached 30%. This could be explained with pozzolanic activity of fly ash. Differences for mixture CCB ranged between 28.7% and 39.1%, while for mixture CRCA they were smaller and ranged between 9.1% and 21.7%.

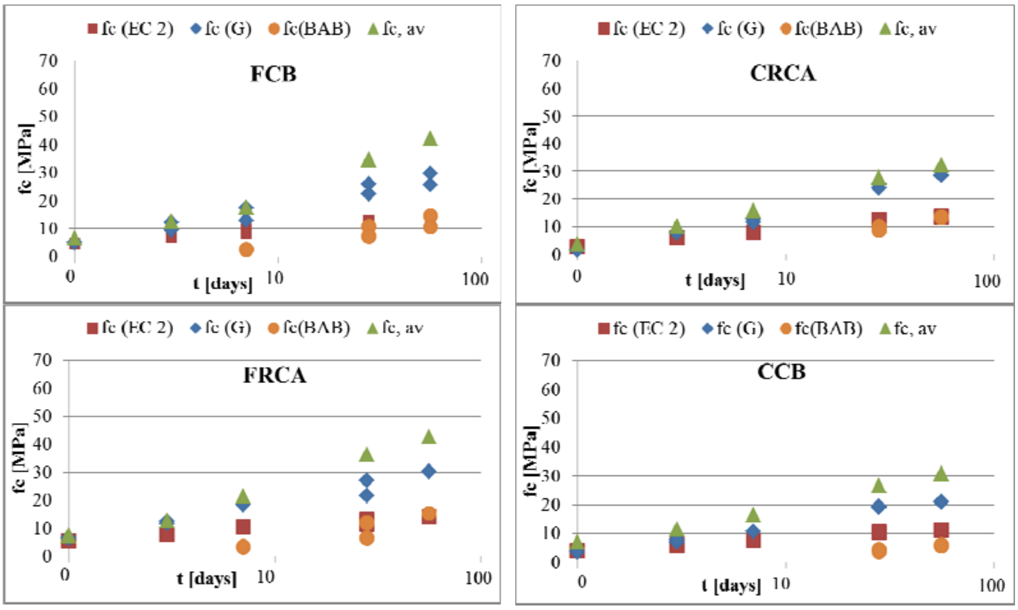

Figure 6. Measured and calculated compressive strength development through time for the series FCB, CCB, FRCA and CRCA

3. Conclusions

- Dynamic modulus of elasticity calculated using UPV method showed higher values than the values of dynamic modulus of elasticity calculated through resonant frequency measurements, as confirmed in literature. Both methods of measurement showed sensitivity for different compositions of self-compacting mortars. The smallest differences, when compared with referent series were found for the mixtures with partial replacement of mineral filler only.
- Strong correlation between dynamic modulus of elasticity and compressive strength was established for all of the series. It was confirmed that coefficient in these correlations depended mostly on the overall mortar composition (through bulk densities of the series).
- Different models that can be found in literature, describing relation between modulus of elasticity and compressive strength of concrete, were applied on the values measured in presented experiment. It was shown that, although values of dynamic modulus of elasticity are higher than values of static modulus used for development of these models, two of them (Eurocode 2 and BAB'87) underestimated values of compressive strength. Model proposed by Gardner showed potential for application in tested materials, since it was sensitive to the changes in composition of the mixtures.
- Future research of the correlation between compressive strength and dynamic modulus of elasticity values for mortars should take into account bulk density of the mixture (parameter that describes differences in the composition of the mortars) and porosity as proposed by Popovics [5]. Further on, different types of cement and mineral fillers and their potential pozzolanic properties also affect this correlation, and therefore should be considered.

- If these correlations are to be improved, non-destructive testing methods such as resonant frequency measurements or ultrasonic pulse velocity measurements could be used for predictions of both compressive strength and modulus of elasticity for different mixtures.

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