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Experimental Determination of Modulus of Elasticity of Concrete by Non-Destructive Ultrasonic Pulse Velocity Method

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Abstract: In this paper are described the experimental researches for determining the modulus of elasticity of concrete by the measured velocity of ultrasonic pulse, using the Non-Destructive Ultrasonic Pulse Velocity Method. Knowing the modulus of elasticity is necessary to be ensured service suitability and acceptable appearance of the designed reinforced concrete structures. The researches were performed on standard test specimens tested on different age of concrete between 3 days and 1126 days. The obtained results were compared to the theoretically calculated according to EN 1992-1-1:2004 and experimentally determined according to EN 12390-13:2013. An analysis for proving the advantages and disadvantages of the non-destructive ultrasonic pulse velocity method compared to EN 12390-13: 2013 has been carried out.

Keywords: Experiment, modulus of elasticity, material density, non-destructive method, ultrasonic pulse velocity method, EN 12504-4:2004.

I. INTRODUCTION

The non-destructive ultrasonic pulse velocity method [1], [2] for determining the modulus of elasticity is becoming increasingly used for determining the properties and quality of provided concrete in concrete and reinforced concrete structures. In this method is used the principle known from physics, that at propagation of mechanical oscillations with frequency from 25 to 200 kHz and small amplitude in reinforced concrete elements elastic deformations occur. The method is fast, easy to use, and is not related to destruction of local areas in the structural elements. It is applicable to all types of building structures, both in the process of their construction and during their exploitation.

Depending on the access to the structural elements and the location of the transmitting transducer and the receiving transducer direct, semi-direct or surface transition could be performed [2].

The dynamic modulus of elasticity $E_{c,din}$ can be determined by the following formula [1], [8]:

1) $E_{c,din} = k\rho_c V_{UP}^2$,

where:

V_{UP} is velocity of propagation of ultrasonic waves in concrete and reinforced concrete elements in [m/s];

k is factor that is assumed to be equal to $(1+\nu)(1-2\nu)/(1-\nu)$ in case of longitudinal waves transition and equal to $2(1+\nu)$ in case of transverse waves transition;

ρ_c is the acoustic density of the material in [kNs^2/m^4]:

2) $\rho_c = \dfrac{\gamma_c}{g}$,

where:

γ_c is the weight per unit volume of the concrete;

g is the gravity acceleration.

For the Poisson's ratios ν the following values can be accepted:

3) $\nu = 0,3$ at age of concrete from 2 days to 14 days;

$\nu = 0,2$ at age of concrete 28 days;

$\nu = 0,15$ at age of concrete equal to or greater than 90 days.

According to [1] the modulus of elasticity of concrete E_c could be determined by the following formula:

4) $E_c = k_l E_{c,din}$,

where k_l is factor, which for low-strength concrete is accepted 0.87 and for high-strength concrete is 0.954.

II. EXPERIMENT – TEST SPECIMENS AND EQUIPMENT

For the researches for modulus of elasticity of the concrete 54 cylindrical test specimens with dimensions 150/150 mm and 27 cubic test specimens with dimensions 150/150/150 mm were produced (Fig.1) according to EN 12390-2:2009 [5], [7]. They were prepared of concrete grade C25/30, fine fraction of coarse aggregate (dmax=12 mm), consistence S3. Test specimens were with precise dimensions, flat and smooth sides, straight edges and corners.

Fig. 1 Specimens for testing according to EN 12504-4:2004 [2] (author's personal archive)

For all the specimens the geometric dimensions and weight is measured, after that the weight per unit volume γ_c is calculated (Fig.2).

Fig. 2 Measuring the geometric dimensions and weight of test specimens (author's personal archive)

Experimental investigations for determining the modulus of elasticity of concrete based on measured velocity of ultrasonic pulse, using the Non-Destructive Ultrasonic Pulse Velocity Method were performed with portable ultrasonic testing instrument type Proceq-TICO [9] with measuring range from 15 to 6550 µsec (Fig.3).

Fig. 3 Determining the modulus of elasticity of concrete with portable ultrasonic testing instrument type Proceq-TICO (author's personal archive)

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III.TEST RESULTS AND DISCUSSION

The modulus of elasticity is obtained according to EN 12504-4:2004 [2] by testing 81 test specimens (3 cubic specimens and 6 cylindrical specimens for each of the test days) at the age of concrete 3rd, 7th, 14th, 28th, 244th, 280th, 293rd, 342nd and 1126th day. For each test specimen 10 measurements were performed. The transmitter and receiver of ultrasonic testing instrument were placed symmetrically against each other. Before each measurement, the equipment is calibrated with calibration rod with known velocity of the ultrasonic pulse.

The modulus of elasticity is also determined experimentally according to EN 12390-13 [3] by testing standard prismatic specimens at the age of concrete 28th, 244th, 280th, 293rd, 342nd and 1126th day. The results of these experiments are published in [6]. The modulus of elasticity is calculated theoretically according EC2 [4] at different age of concrete by the following formula:

(5) $$E_{cm}(t) = \left(f_{cm}(t) / f_{cm} \right)^{0,3} E_{cm} \left[MPa \right],$$

where $E_{cm}(t)$ and $f_{cm}(t)$ are the values at the age t days, E_{cm} and f_{cm} are the values at the 28th day of the modulus of elasticity and mean cylindrical compressive strength of concrete. The relation between $f_{cm}(t)$ and f_{cm} is determined by:

(6) $$f_{cm}(t) = \beta_{cc}(t) f_{cm} \; [MPa].$$

The factor $\beta_{cc}(t)$ is calculated by:

(7) $$\beta_{cc}(t) = e^{s\left(1-\sqrt{\frac{28}{t}}\right)},$$

where s is factor, depending on the type of cement.

In Table 1 are given the mean values of measured velocities of propagation of ultrasonic waves at different age of concrete.

Table 1

Mean values of measured velocities of propagation of ultrasonic waves and

Age of concrete	Days	3	7	14	28	244	280	293	342	1126
Mean velocities of propagation of ultrasonic waves	m/s	3811.83	4081.33	4148.67	4229.83	4263.00	4288.50	4307.50	4329.17	4368.67
Probable modulus of elasticity of the concrete	MPa	22418.69	25481.32	26226.98	32916.24	34825.82	35496.71	35640.51	35936.99	36547.68

Probable modulus of elasticity at different age of concrete

Fig. 4 shows graphical dependencies of mean values of modulus of elasticity of concrete for each day of research as follows:

a) with blue line is shown the experimentally determined modulus of elasticity with ultrasonic pulse velocity method according to EN 12504-4:2004;

b) with red line - experimentally determined modulus of elasticity according to EN 12390-3:2009;

c) with green line – the modulus of elasticity calculated according to EN 1992-1-1:2004.

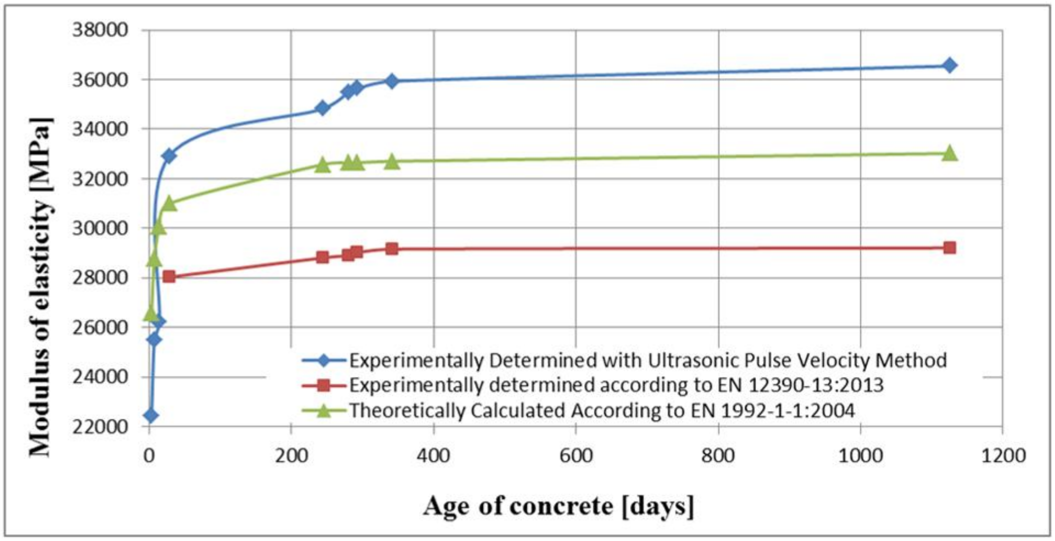

Fig.4 Dependencies of mean values of modulus of elasticity at different age of concrete

In table 2 are given the mean values of the obtained according the two standards [2], [3] and calculated according to [4] modulus of elasticity of concrete at each day of testing and the error, in percentage, between the experimentally determined and theoretically calculated values.

From the three graphical dependencies, it can be seen that the modulus of elasticity increases with increasing the age of the concrete. For age of concrete up to 28th days the determined by ultrasonic pulse velocity method probable modulus of elasticity is smaller than the theoretically calculated according to EC2. For age of concrete ≥ 28 days the theoretically calculated is greater than the experimentally determined according to [2]. Experimentally determined modulus of elasticity according to EN 12390-13:2013 for age of concrete ≥ 28 days is always smaller than those according to EC2.

The errors (Table 2) of experimentally determined modulus of elasticity with ultrasonic pulse velocity method related to the theoretically calculated by formulas (5), (6) and (7) are between 11.4% and 15.6% for age of concrete < 28 days and between 6.2% and 10.7% for age of concrete ≥ 28 days. The errors of experimentally determined modulus of elasticity according to EN 12390-13:2013 related to the theoretically calculated according to EC2 are between 9.6% and 11.6% for age of concrete ≥ 28 days.

Table 2
Mean values of the experimentally obtained and theoretically calculated modulus of elasticity of concrete and the relative error for each of the days

Age of concrete	Modulus of elasticity			Error	
	EN 12504-4	EN 12390-13	EN 1992-1-1	EN 12504-4	EN 12390-13
[Days]	[MPa]	[MPa]	[MPa]	[%]	[%]
3	22418.69	-	26572.13	15.6	-
7	25481.32	-	28760.11	11.4	-
14	26226.98	-	30051.79	12.7	-
28	32916.24	28033.3	31000.00	6.2	9.6
244	34825.82	28809.1	32576.11	6.9	11.6
280	35496.71	28902.4	32631.19	8.8	11.4
293	35640.51	29022.5	32648.56	9.2	11.1
342	35936.99	29160.4	32704.93	9.9	10.8
1126	36547.68	29208	33021.48	10.7	11.5

IV. CONCLUSIONS

In this paper are compared the experimentally determined modulus of elasticity of concrete according to EN 12504-4:2004 and EN 12390-13:2013 with theoretically calculated results at different age of concrete with grade C25/30. The theoretically calculated modulus of elasticity according to [4] at age of concrete ≥ 28 days are with values between the experimentally determined values according to [2] and [3]. The small error percentage of ultrasonic pulse velocity method, commensurable with error percentage of experimentally determined modulus of elasticity of concrete according to [3], the opportunity for real time control, the automation of the method, the continuous data recording, the portability of the equipment, the negligible power consumption, the possibility of unilateral access control and the preservation of integrity of tested reinforced concrete elements are allowing a wider application of the ultrasonic pulse velocity method for diagnostics and control.

V. ACKNOWLEDGMENT

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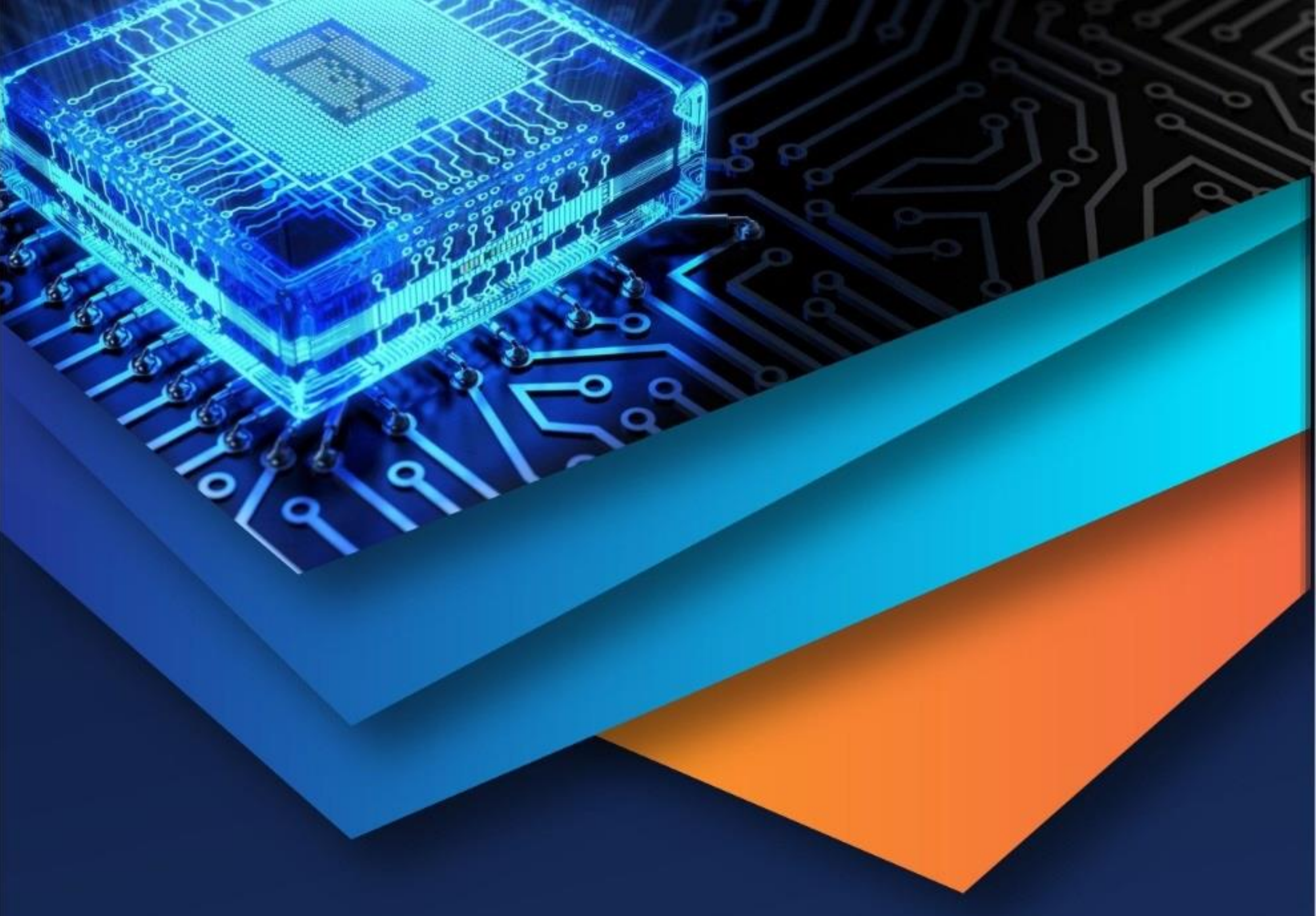

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