

APPLICATION OF THE ULTRASONIC METHOD IN EVALUATION
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Abstract. Application of nondestructive methods in assessing the properties of materials and mixes is very popular because of their simplicity and noninvasive nature. The ultrasonic method is, as one of nondestructive methods, used for more than 60 years in determining the properties of concrete mixes. However, only recently it has been applied application in studies of the stabilization mixes intended for road construction. The ultrasonic method is based on measurement of the travel time of longitudinal ultrasonic waves through the sample. In this paper, the investigation of stabilized mixes containing sand from river Drava stabilized with cement and fly ash are presented. The aim of the research was to determine the impact of changes in the composition of mixes and in the regime of care on the density, compressive strength and ultrasonic velocity. An additional goal was to analyze the relationship between the investigated properties of mixes and the ultrasonic velocity. The compressive strength of the stabilized mixture is determined by the destructive method according to *Croatian Standards HRN.U.B1.030 Unconfined Compressive Strength* as the average stress in a sample during uniaxial compression testing at the ultimate force. Testing of density and compressive strength of mixes and determination of the ultrasonic speed has been performed after 7, 28 and 90 days of curing at four different temperatures: 5 °C, 15 °C, 25 °C and 35 °C. The obtained results indicated the direct influence of fly ash quantity on the observed properties. Increase in the amount of fly ash caused a decrease in the mixture compressive strength, its density and ultrasonic velocity. A significant influence of treatment temperature on the compressive strength, density and ultrasonic velocity was also observed. Finally, correlation between density and ultrasonic velocity, as well as compressive strength and ultrasonic velocity was established. Exponential relationship between the compressive strength of stabilized mixes and ultrasonic velocity proved to be very strong, and similar to those obtained in previous studies by other researchers. Test results showed that the ultrasonic method can be useful in assessing properties of stabilized mixes.

Keywords: properties, fly ash stabilized mixes, density, compressive strength, ultrasonic pulse velocity, regression models.

1. Introduction

Base courses stabilized by cement or other hydraulic binders (fly ash, slag) are widely used. They are equally represented in asphalt pavement structures, in which they act as one of the most important elements in terms of capacity, as well as in concrete pavements structures in which they prevent the emergence of material “pumping”. Today’s pavement structures, especially those designed for heavy traffic loads, are almost always constructed with layers stabilized with some type of hydraulic binder.

Stabilized mixes containing standard binders as cement and lime were investigated frequently, while mixes with non standard binders as fly ash much less. This „modern pozzolan“ (also waste material) has been used more often in the design concrete mixes (Bai, Gailius 2009; Ko-

sior-Kazberuk, Lelusz 2007). Multiyear investigations results have shown that the addition of fly ash to the cement mixes improves their properties.

Mechanical properties of cement stabilized mixes are commonly defined by its compressive strength, which is defined as the average strain in a sample exposed to uniaxial pressure at the failure force. Cement stabilized materials are usually tested for the compressive strength after 7 and 28 days of curing, while for materials that have extended periods of bonding (e.g. puccolans as fly ash), the period to achieve the required compressive strength can be even longer.

The use of nondestructive testing (NDT) methods in evaluation of a cement mixes properties is very popular because of their simplicity, speed, and noninvasive nature. Using a NDT method it is not possible to obtain direct

information on the strength of the material. Instead, for a proper assessment of the strength it is necessary to establish correlations between NDT test results and the compressive strength obtained from some destructive testing.

A popular NDT method is ultrasonic method, which is based on measurement of the travel time of longitudinal ultrasonic waves through the sample. The ultrasonic method is equally applicable in evaluation of constructed structures and laboratory testing, where it can reduce the number of samples required for testing. The results obtained by the ultrasonic method are certainly an important indicator of the material quality, but also can be used indirectly for establishing correlations with other material properties (Naik et al. 2004).

The ultrasonic method has been used in determination of properties of concrete mixes for many years. The method has been developed at the same time by Leslie and Cheesman (1949) in Canada and Jones (1949) in England. A large number of tests of concrete mixture have been made using ultrasound. Many researchers applied the ultrasonic method in evaluation of properties of concrete mixes: Malhotra (1976), Demirboğa et al. (2004), Solís-Carcano, Moreno (2007), Lin et al. (2007). Assessment of properties of stabilized mixes using ultrasound was much less common. Jones (1966) was among the first researchers who used ultrasound to evaluate elastic properties and strength of cement stabilized mixes. Yesiller et al. (2002) used an ultrasonic method to evaluate properties of a mixture of cement, fly ash and lime, while De Castro Ferreira, Camarini (2001) used it to evaluate mechanical properties of sand and lime mixes.

The goal of this paper is to describe the assessment of properties of stabilized mixes using ultrasonic method and to establish a correlation between the compressive strength and ultrasonic velocity. This paper describes a part of the extensive research on stabilization mixes conducted at Faculty of Civil Engineering Osijek (Dimter 2005), Croatia.

2. Materials and test methods

2.1. Materials

For the purpose of this research, stabilization mixes are designed containing sand from the river Drava and binders composed of cement and fly ash. The basic granular material used is sand from the river Drava. This sand is of uniform size distribution of a grain size $D_{50} = 0.3$ mm,

gray-brown color, degree of unevenness $U = \frac{d_{60}}{d_{10}} = 2$, and

California Bearing Ratio of CBR = 8–12%.

Cement CEM II/BM (PS) 32.5 N (EN 197-1:2005 *Cement – Part 1: Composition, Specifications and Conformity Criteria for Common Cements*) was used as a hydraulic binder. In addition to cement, fly ash of a composition belonging to a group of silicate fly ash was used (EN 142277-4:2004 *Hydraulically Bound Mixes-Specifications – Part 4: Fly Ash for Hydraulically Bound Mixes*).

This means that, because of a small share of CaO (mass 2.5%), it has no capability of binding. Instead, it can be used only in combination with other hydraulic binder. The chemical contents of the fly ash used during this study are shown below, expressed as percentages of mass of individual components (mass, %): $\text{SiO}_2 = 53.0$; $\text{Al}_2\text{O}_3 = 29.0$; $\text{Fe}_2\text{O}_3 = 10.0$; $\text{CaO} = 2.5$; $\text{MgO} = 1.5$; $\text{K}_2\text{O} = 0.2$; $\text{Na}_2\text{O} = 2.0$.

2.2. Specimen preparation and curing

The following groups of stabilized mixes have been prepared:

I A – sand +10% binder (0% fly ash +100% cement) – control mixture;

I B – sand +10% binder (25% fly ash +75% cement);

I C – sand +10% binder (50% fly ash +50% cement);

I D – sand +10% binder (75% fly ash +25% cement);

II A – sand +14% binder (0% fly ash +100% cement) – control mixture;

II B – sand +14% binder (25% fly ash +75% cement);

II C – sand +14% binder (50% fly ash +50% cement);

II D – sand +14% binder (75% fly ash +25% cement).

The binder contents (10% and 14%) were taken by weight of the dry sand. Based on the results of previous studies (Dimter 2005) compaction energy $E = 1.0$ MJ/m³ was selected for samples preparation, at which the max dry weight of $\gamma_{dmax} = 1729$ t/m³ was achieved at an optimum humidity $w_{opt} = 12.6\%$. Samples were prepared in cylindrical molds of a 10 cm diameter, 20 cm height, and compacted by hand with Proctor compactor in five equal layers, with the number of impacts adapted to the selected compaction energy. After the preparation, samples were extruded using a hydraulic press from the mold and left one day at room temperature. The samples were afterwards placed in four environmental chambers at curing temperatures of 5 °C, 15 °C, 25 °C and 35 °C and constant humidity of 80%. Samples were cured for 7, 28 and 90 days, after which the test were performed and density, compressive strength and ultrasonic velocity measured.

2.3. Test methods

Density of stabilization mixes depends on the density of its components and the compactness of a mixture. The diameter of the specimen, the specimen height and weight were measured after a prescribed curing pattern and just before the measurement of the ultrasonic velocity and determination of the compressive strength. Density of a stabilization mixture was calculated according to the expression:

$$\rho = \frac{m}{V}, \quad (1)$$

$$V = \frac{\pi d^2}{4} h, \quad (2)$$

where m – specimen mass, kg; V – specimen volume, m³; d – specimen diameter, m; h – specimen height, m.

The compressive strength of a mixture depends on the properties of materials and the curing conditions, and is defined as the average stress in a specimen during the uniaxial compression testing at the ultimate force (*HRN U.B1.030 Jednoosna čvrstoća* [Unconfined Compressive Strength]).

The specimen for testing the compressive strength was placed in a press with a constant force rate until failure. The failure force is recorded and from it the compressive strength of the stabilized mixture is calculated from:

$$f_c = \frac{P}{A}, \quad (\text{MN/m}^2), \quad (3)$$

where P – compressive force of fracture, MN; A – specimen surface area, m^2 .

The ultrasonic velocity measurement is defined by *Standard HRN EN 12504-4 Ispitivanje Betona – 4.dio: Određivanje Brzine Ultrazvučnog Impulsa* [Concrete Testing – Part 4: Determination of Ultrasonic Impuls Velocity] and the method is shown in Fig. 1.

Pulse generator generates electrical impulses of a specific frequency. The transmitter converts them into elastic waves that propagate through a sample. The receiver on the other side of the specimen receives the mechanical energy of the propagating waves and turns it into electrical energy of the same frequency. The time of passage of ultrasound through the specimen is measured electronically and is registered in the oscilloscope (T).

Since the velocity of ultrasonic pulses in cement stabilized mixes is not frequency dependent, testing can be conducted using impulses of a frequency most appropriate for the certain material and geometry. For cement stabilized materials, impulses in a frequency range of 20–250 kHz can be used, which correspond to impulses of wavelengths 115–3.6 mm.

Ultrasonic velocity was calculated from the Eq (4):

$$v = \frac{L}{T}, \quad (4)$$

where v – ultrasonic velocity, km/s; L – specimen length, m; T – travel time of ultrasound through the specimen μs .

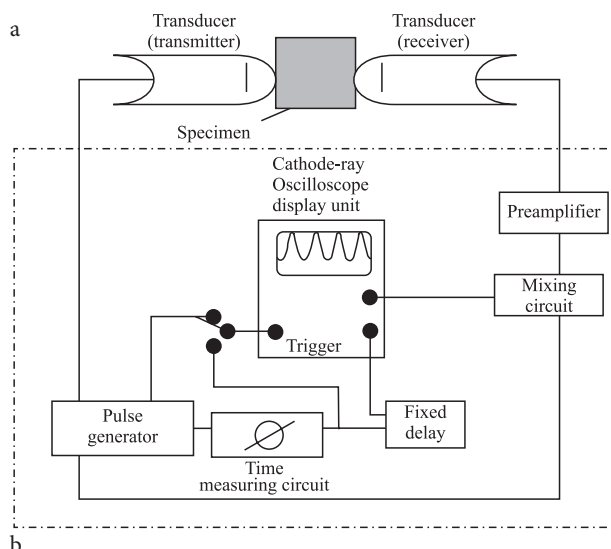


Fig. 1. Ultrasonic velocity measurement: a – schematic overview; b – measuring equipment

3. Testing results and discussion

Table 1 presents part of the tests results for testing mixes' density, compressive strength and ultrasonic velocity for min and max curing temperatures of 5 °C and 35 °C and curing periods of 7, 28 and 90 days. Shown values are average values of four samples (density) or three samples (ultrasonic velocity and compressive strength).

Table 1. The results of density, compressive strength and ultrasonic velocity tests

7 days group	5 °C			35 °C		
	ρ , kg/m ³	f_c , MN/m ²	v , km/s	ρ , kg/m ³	f_c , MN/m ²	v , km/s
I A	1846.78	1.12	1.26	1755.20	2.12	1.87
I B	1763.26	0.42	1.14	1636.57	1.15	1.38
I C	1803.26	0.33	1.00	1715.76	0.90	1.44
I D	1783.77	0.12	0.77	1665.02	0.31	1.12
II A	1887.19	1.50	1.36	1789.81	3.73	2.17
II B	1828.28	0.82	1.53	1706.02	2.03	1.78
II C	1823.72	0.54	1.17	1711.20	1.37	1.74
II D	1793.22	0.24	0.90	1664.31	0.54	1.33

Continued Table 1

28 days group	5 °C			35 °C		
	ρ , kg/m ³	f_c , MN/m ²	v , km/s	ρ , kg/m ³	f_c , MN/m ²	v , km/s
I A	1802.49	1.92	1.98	1706.17	2.72	1.94
I B	1817.27	0.95	1.57	1691.25	1.90	1.65
I C	1753.35	0.66	1.36	1670.34	1.18	1.43
I D	1729.09	0.20	0.88	1630.86	0.37	1.08
II A	1845.74	2.58	2.31	1765.04	4.09	2.12
II B	1853.03	1.76	2.08	1735.38	3.07	2.07
II C	1781.58	1.21	1.72	1672.78	2.00	1.78
II D	1787.72	0.38	1.15	1660.89	0.73	1.43
90 days group	5 °C			35 °C		
	ρ , kg/m ³	f_c , MN/m ²	v , km/s	ρ , kg/m ³	f_c , MN/m ²	v , km/s
I A	1762.12	2.34	2.20	1720.74	2.00	1.89
I B	1736.82	2.45	2.00	1693.15	1.98	1.70
I C	1712.14	1.12	1.70	1660.85	1.68	1.49
I D	1664.45	0.93	1.49	1610.80	0.59	0.80
II A	1811.50	4.04	2.46	1761.65	4.09	2.13
II B	1796.77	3.35	2.36	1722.22	3.07	2.03
II C	1756.46	2.04	2.08	1699.22	2.00	1.74
II D	1721.02	0.99	1.53	1669.24	0.73	1.38

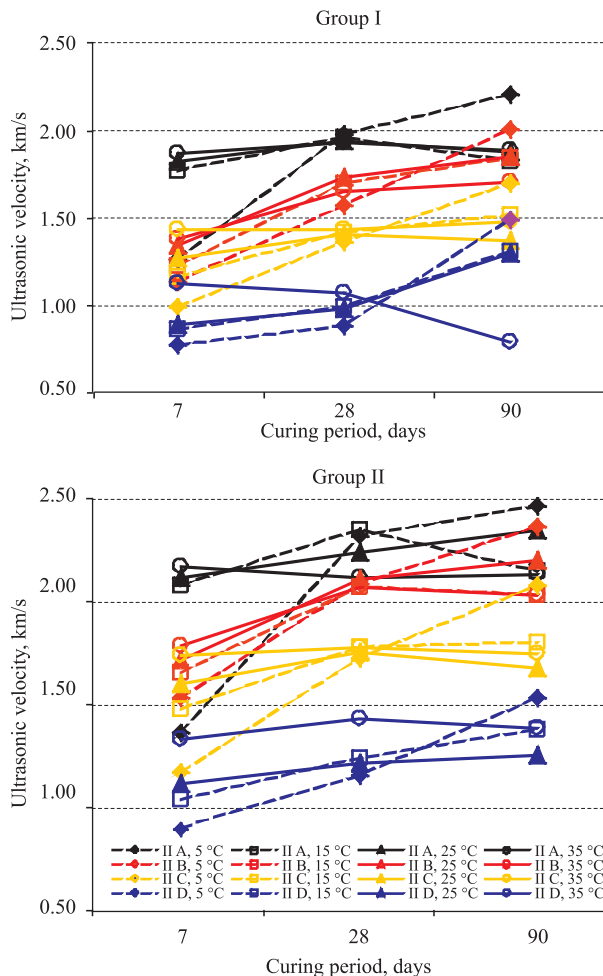


Fig. 2. Influence of the curing period on ultrasonic velocity

3.1. Relationships between ultrasonic velocity and curing period

Influence of the curing period on the ultrasonic velocity of stabilized mixes is shown in Fig. 2.

Ultrasonic velocity in both groups of stabilized mixes behaved very similarly, it increased as the curing period increased. Stabilized mixes of a group II with a 14% binder had higher ultrasonic velocities.

Both compressive strength and ultrasonic velocity vary with the proportion of fly ash in the binder and the curing temperature. Ultrasonic velocity was higher for a mixture A with pure cement and lowest ultrasonic velocities had a mixture D with 75% of fly ash in the binder. This phenomenon can be explained by the setting time of different binders in stabilization mixes. Specifically, for pozzolanic reaction of fly ash in the binder a longer curing period is needed (over 90 days), while cement in stabilized mixture reacts immediately. Content of CaO in the fly ash of 2.5 mass % was certainly insufficient to create significant pozzolanic reaction contributes to this fact.

Ultrasonic velocity is influenced by the curing temperature, which is especially pronounced for the curing period of 7 days. Samples cured at a 5 °C temperature had lower ultrasonic velocities than the samples of the same mixture cured at 35 °C. The influence of different temperature treatment on the velocity decreased as the curing time increased.

Range of ultrasonic velocity for various curing periods, compositions and treatment temperatures is shown in Table 2.

Table 2. Range of ultrasonic velocity results for different curing periods

Curing period	Ultrasonic velocity, km/s
7 days	0.91 to 1.93
28 days	0.99 to 2.25
90 days	1.22 to 2.27

3.2. Relationship between ultrasonic velocity and density of stabilized mixes

Density of stabilization mixes depends on the density of its components and the mixture compactness. Since the modulus of elasticity of stabilization mixes increases as the density increases, the ultrasonic velocity increases too. The increase of cement content in the mixes (10 mass %, 14 mass %) resulted in increased density and consequently higher values of ultrasonic velocity.

Increase in the proportion of fly ash in the binder (from 0% to 75%), resulted in decreased density, and lower ultrasonic velocity.

The diagram in Fig. 3 shows the relationship between the density of all groups of stabilization mixes and ultrasonic velocity for the curing period of 90 days and all curing temperatures. The density and ultrasonic velocity are well correlated ($R^2 = 0.81$ for group I and $R^2 = 0.86$ for group II), considering that different mixture groups were analyzed for all curing temperature treatment.

The effect of the curing temperature on the density, especially during the first 7 days was evident, as shown in Fig. 4. The highest densities had stabilized mixes treated at a 5 °C temperature. As temperature increased, the mixture density decreased. This phenomenon can be explained by the fact that stronger evaporation occurs as curing temperature increases and the relationship between mass and volume of the specimen changes.

As the curing period is extended to 90 days, the effect of curing temperature on the density and ultrasonic velocity is minor. Fig. 5 presents the diagrams for a mixture

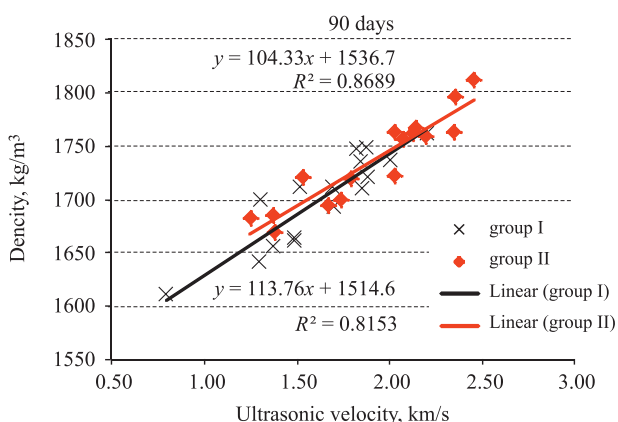


Fig. 3. Relationship between density and ultrasonic velocity for stabilized mixes

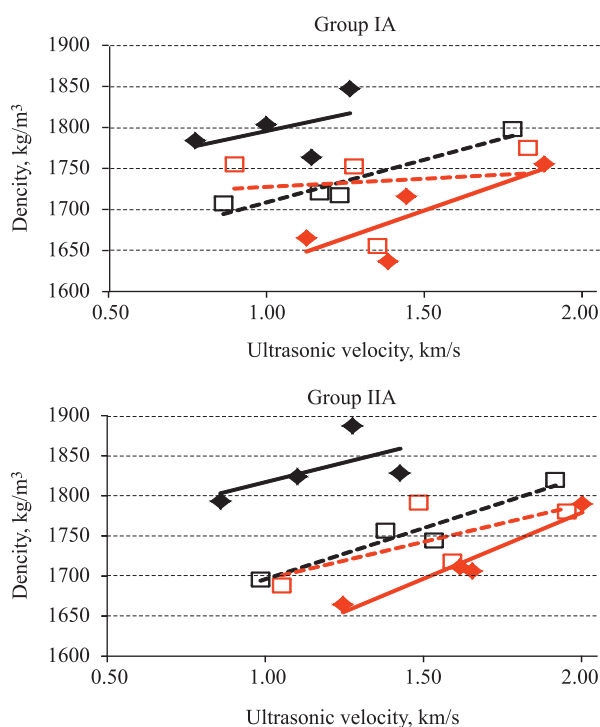


Fig. 4. Relationships between density and ultrasonic velocities of stabilized mixes after curing of 7 days: \blacklozenge 5 °C, \square 15 °C, \square 25 °C, \blacklozenge 35 °C, — Linear (5 °C), - - - Linear (15 °C), - - - Linear (25 °C), — Linear (35 °C).

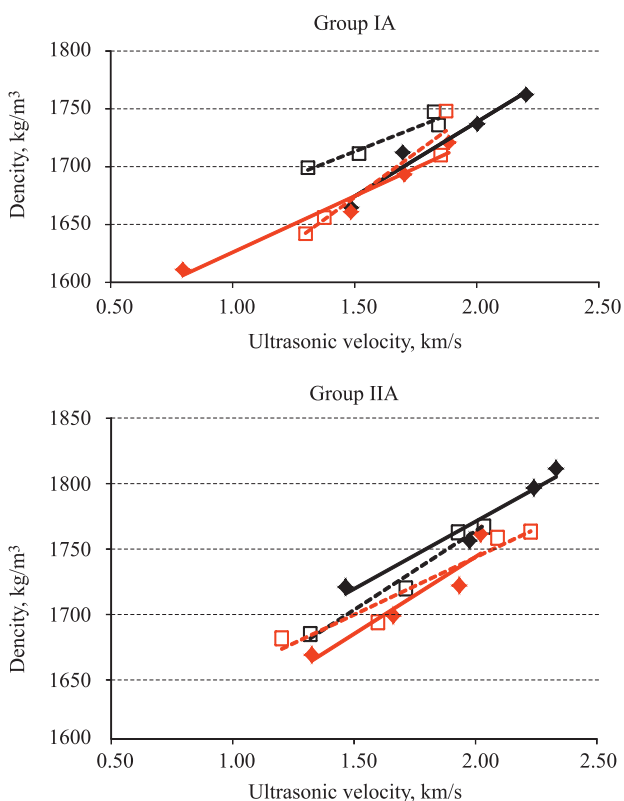


Fig. 5. Relationships between density and ultrasonic velocities of stabilized mixes after curing of 90 days: \blacklozenge 5 °C, \square 15 °C, \square 25 °C, \blacklozenge 35 °C, — Linear (5 °C), - - - Linear (15 °C), - - - Linear (25 °C), — Linear (35 °C).

Table 3. Correlations between density and ultrasonic velocity

Temperature, °C	Group IA		Group IIA	
	7 days	90 days	7 days	90 days
5	$y = 82.553x + 1713.2$	$y = 128.02x + 1482.4$	$y = 88.538x + 1723.4$	$y = 96.203x + 1568.8$
	$R^2 = 0.2346$	$R^2 = 0.9556$	$R^2 = 0.3725$	$R^2 = 0.9578$
15	$y = 104.7x + 1604.0$	$y = 82.906x + 1588.7$	$y = 114.91x + 1574.5$	$y = 112.94x + 1526.5$
	$R^2 = 0.9046$	$R^2 = 0.9311$	$R^2 = 0.9249$	$R^2 = 0.9651$
25	$y = 20.144x + 1707.4$	$y = 153.84x + 1442.6$	$y = 83.815x + 1607.4$	$y = 82.024x + 1571.3$
	$R^2 = 0.0203$	$R^2 = 0.9171$	$R^2 = 0.4849$	$R^2 = 0.9407$
35	$y = 134.98x + 1496.9$	$y = 97.227x + 1528.7$	$y = 148.0x + 1458.2$	$y = 110.31x + 1512.3$
	$R^2 = 0.6309$	$R^2 = 0.9627$	$R^2 = 0.9419$	$R^2 = 0.8968$

re of control specimens cured for 90 days and at different temperatures. The obtained results indicate good correlation between the density and ultrasonic velocity ($R^2 = 0.91$ – 0.96 for a group IA or $R^2 = 0.89$ – 0.96 for the group IIA). Correlations between density and ultrasonic velocity are shown in Table 3.

3.3. Relationship between ultrasonic velocities and compressive strength for stabilized mixes

The compressive strength of a stabilized mixture depends on the properties of materials and testing conditions. Material properties that affect the compressive strength are: type and binder content, type and quality of grain stone material, moisture content, compactness, curing period and temperature.

Test results indicate direct influence of fly ash content in the binder and curing temperature on the compressive strength and ultrasonic velocity of stabilization mixes. As the content of fly ash in the binder increases (from 0% to 75%), the compressive strength decreases, as well as the ultrasonic velocities (Table 4). Max ultrasonic velocities were achieved in mixes without fly ash.

The effect of curing temperature, as well as of density, is especially emphasized for samples with curing periods of 7 and 28 days. The compressive strength is higher for higher curing temperatures. For samples that had extended curing, this relationship is changing with the curing period. Therefore, it can be concluded that the stabilized mixes cured at lower temperatures get higher later strength. Similar behavior was observed for the measured ultrasonic velocity: greater velocities were observed for higher curing temperatures (35 °C), especially for the curing period of 7 days. The ultrasonic velocity range for all tested specimens of stabilization mixes and all curing temperatures and curing periods is shown in Table 4.

Besides being an indicator of the quality of stabilization mixes, or a performance indicator, the ultrasonic velocity can be correlated to the compressive strength of mixes. The relationship between the compressive strength and ultrasonic velocity was examined in two models:

$$f_c = ae^{bv}, \quad (5)$$

Table 4. Average ultrasonic velocity for specified groups of mixes

Designations of a mixes	Ultrasonic velocity, km/s
Mixture A (0% fly ash)	2.01 to 2.25
Mixture B (25% fly ash)	1.74 to 2.06
Mixture C (50% fly ash)	1.48 to 1.81
Mixture D (75% fly ash)	1.35 to 1.36

$$f_c = av^b, \quad (6)$$

of which model $f_c = ae^{bv}$ was selected for the interpretation because it satisfies all groups of results (model $f_c = av^b$ satisfied only certain groups of results).

The relationship between the compressive strength and ultrasonic velocity for all stabilized mixes and for different curing periods can be seen in the diagram in Fig. 6.

The diagrams in Fig. 7 show the relationship between the compressive strength and ultrasonic velocity, as a function of fly ash percentage in the binder for mixes B (25% fly ash) and C (50% fly ash).

A strong relationship between compressive strength and ultrasonic velocity can be observed in the presented results, with a high coefficient of determination for most of the analyzed combinations. The strongest relationship was established for a control mixture without fly ash in the binder. Since coefficients of determination were lower for mixes C and D, it can be concluded that the relationship between the compressive strength and ultrasonic velocity are affected by the percentage of fly ash in the binder.

The analysis of the effect of curing temperature showed that all mixes that are cured at 35 °C have slightly lower coefficient of determination. Therefore, a small number of data can be mathematically described by the selected model. From the given indicators, it can be concluded that the relationship between the compressive strength and ultrasonic velocity depends on both the fly ash percentage in the binder and a high curing temperature. Correlations between compressive strength and ultrasonic velocity are shown in Table 5.

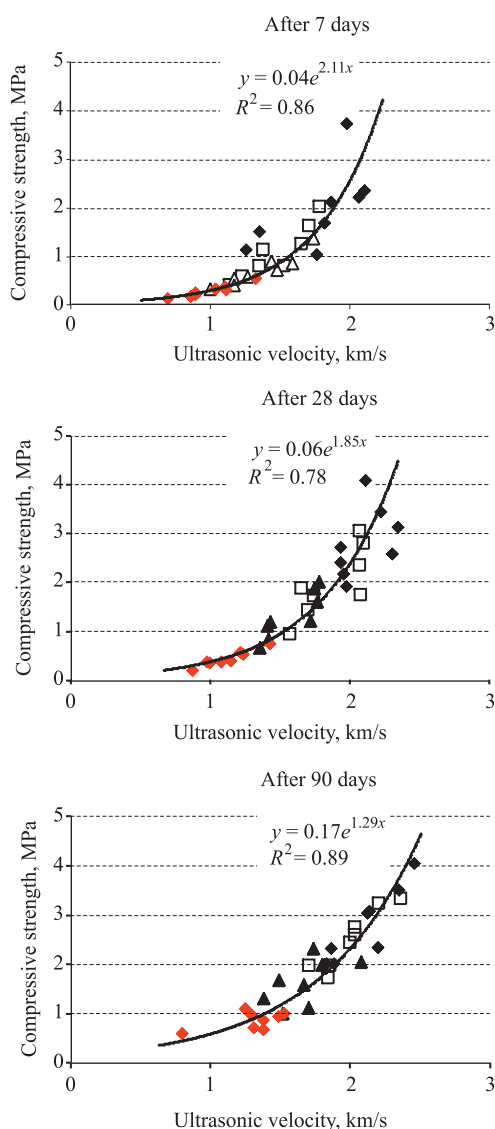


Fig. 6. Relationship between compressive strength and ultrasonic velocity for all mixes and curing periods: ♦ amount of fly ash 0%, □ amount of fly ash 25%, ▲ amount of fly ash 50%, ◆ amount of fly ash 75%.

Table 5. Correlations between compressive strength and ultrasonic velocity

Temperature, °C	Group B	Group C
5	$y = 0.0949e^{1.4525x}$ $R^2 = 0.8841$	$y = 0.0851e^{1.5078x}$ $R^2 = 0.9765$
15	$y = 0.0707e^{1.7628x}$ $R^2 = 0.9237$	$y = 0.0632e^{1.775x}$ $R^2 = 0.8712$
25	$y = 0.0898e^{1.6881x}$ $R^2 = 0.9259$	$y = 0.1271e^{1.5105x}$ $R^2 = 0.5659$
35	$y = 0.3277e^{1.0311x}$ $R^2 = 0.9319$	$y = 0.1727e^{1.4251x}$ $R^2 = 0.4891$

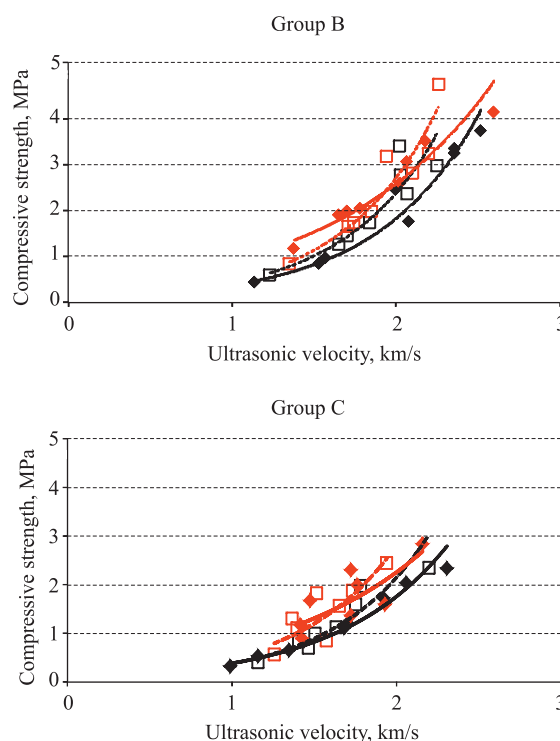


Fig. 7. Compressive strength and ultrasonic velocity for mixes: ◆ 5 °C, □ 15 °C, □ 25 °C, ◆ 35 °C,

4. Conclusions

The following conclusions can be made with respect to the relationship of density, compressive strength, fly ash percentage in binder and curing temperature, and ultrasonic velocity of stabilized mixes.

Ultrasonic velocity is a good indicator of density and compressive strength of stabilized mixes:

As the density of stabilized mixes increases, modulus of elasticity and, thus, ultrasonic velocity increases too. The increase of binder content in the mixture (10 mass.%, 14 mass.%) results in increased density and ultrasonic velocity. The increase of the fly ash percentage in binder (from 0% to 75%), results in decreased density and ultrasonic velocity. Based on the results of the statistical analysis, the reduction of density of the mixes with respect to the percentage of fly ash in the binder, after seven days of curing at different temperatures ranged from 2.7% to 5.3%. The density reduction is more pronounced for the mixes with 14% of binder. For samples cured for 28 days, reduction in density ranged from 2.4% to 5.6%, while for samples cured 90 days reduction in density accounted for 1.8% to 4.5%.

As the curing period increases, the compressive strength and ultrasonic velocities increases. The increase in the fly ash percentage in binder (from 0% to 75%) causes a decrease in the compressive strength and ultrasonic velocity. Max ultrasonic velocities and compressive strengths had the control mixes A without fly ash, of which

mixes D with 75% of fly ash in binder had the lowest ones. Beside the percentage of fly ash, treatment temperature influences the compressive strength and ultrasonic velocity. The reduction of speed of ultrasound with respect to the percentage of fly ash in the binder, and after seven days of curing at different temperatures, was for all mixes 23–38%. The reduction was 17–35% for samples tested after 28 days, and 14–29% for samples tested after 90 days. Reduction of the compressive strength with respect to the fly ash percentage in the binder, for seven days of curing at different temperatures, was from 59% to 74%. It was 48% to 68% for samples tested after 28 days, and 29% to 56% for samples tested after 90 days.

A strong correlation between compressive strength and ultrasonic velocity was presented using a model $f_c = ae^{bv}$. Mixes A had the highest coefficient of determination of $R^2 = 0.99$ and the mixes D the lowest of $R^2 = 0.78$. Stated values refer to samples with lower curing temperatures. For all the stabilized mixes with a curing temperature of 35 °C, regardless of the composition, slightly lower values of the coefficient of determination were obtained.

The ultrasound velocity is an important indicator of the quality of the mix. This is illustrated by the results for the four mix types: mixes A without fly ash (100% cement) had an average ultrasound velocity from 2.01 km/s to 2.25 km/s, mixes B with 25% fly ash from 1.74 km/s to 2.06 km/s, mixes C, with 50% fly ash, from 1.48 km/s to 1.81 km/s, and the weakest mixes D, with 75% fly ash in the binder, had a velocity from 1.35 km/s to 1.36 km/s.

Finally, the results of this work have shown that the properties of stabilized mixes are highly influenced by the amount of fly ash in binder and the curing temperature. To obtain a high quality mix, it is recommended that the quantity of fly ash in the binder be limited to 25%.

All the stated conclusions are valid for the materials used. However, those can serve as an orientation in examination of properties of other, similar materials. Finally, the ultrasonic method has proven to be useful when assessing properties of stabilized mixes, and certainly a good way to reduce the number of samples typically required for a standard, destructive testing.

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