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ORIGINAL PAPER

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IMPACT OF CURING PROCESS ON ULTRASONIC PULSE VELOCITY IN STABILIZED SOILS

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ABSTRACT

The process of care of soils stabilized with hydraulic binder affects the results of destructive and non-destructive tests. The process itself depends on the country performing stabilization. This study investigated the effect of immersion of stabilized soil samples during the curing process on the ultrasonic pulse velocity. The study showed an increase in velocity of 12.9% in samples immersed in water for seven days. The paper presents test results for seven methods of soil treatment.

Key words: ultrasonic pulse velocity, soil stabilized, curing period

INTRODUCTION

Soil stabilization is the alteration of the properties of locally available soil to improve its engineering properties (Ampera & Aydogmus, 2005). The concept is to mix the soil with an additive, resulting in increased usefulness of the mixture (Firoozi, Guney Olgun, Firoozi & Baghini, 2017). The process of stabilization can be grouped into three main categories: traditional stabilizers (lime, cement and fly ash), byproduct stabilizers (cement kiln dust, lime kiln dust), and nontraditional stabilizers (sulfonated oils, potassium compounds, polymers) (Petry & Little, 2002). Of the stabilizers listed, cement is most commonly used to improve the mechanical properties of soils (Chew, Kamruzzaman & Lee, 2004; Consoli, Foppa, Festugato & Heineck, 2007; Ayeldeen, Hara, Kitazume & Negm, 2016). These materials are commonly used in road structures, including as flexible pavement elements. This kind of pavement can be divided into two characteristic layers with different mechanical properties and performance (Nikolaides, 2015): unbound or hydraulically bound layers of aggregate, laid on top of a subgrade, and bound asphalt layers, laid on top of the previous layer set. Hydraulically bound mixtures (HBM) are used as a base course and sub-base course elements. In cases where weak soils are in place, HBMs are sometimes used for the capping layer. The full classification of HBM is defined in the European Standards. In the case of mixtures using cement as a binder, two basic types of HBM can be classified: cement-bound granular mixtures (CBGM) according to the standard PN-EN 14227-1 (Polski Komitet Normalizacyjny [PKN], 2013) and soil treated with cement binder according to the standard PN-EN 14227-15 (PKN, 2015). Where the first type is often used for base and sub-base courses, the second type is more commonly used for capping layer or sub-base courses. For the determination of properties of hydraulically bonded mixtures, destructive tests such as the determination of unconfined compressive strength (*UCS*) or indirect tensile strength (*ITS*) can be performed. Standards describing

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HBM focus on destructive testing, thus marginalizing non-destructive testing (NDT), which can also be used to determine the mechanical properties of the material being tested or detect defects without changing the structural integrity of the specimen (Dwivedi, Vishwakarma & Soni, 2018). One of the basic non-destructive testing techniques is ultrasonic pulse velocity (*UPV*). This method has been used in construction since the second half of the 20th century (Malhotra & Carino, 2004). Ultrasonic pulse velocity testing involves measuring the time it takes for a wave to pass through the test medium. Several types of ultrasound waves can be distinguished, including compressional waves, shear waves, surface waves, and lamb waves (Malhotra & Carino, 2004; Ensminger & Bond, 2011). The test is performed at frequencies between 20 kHz and 1 GHz (Mandal, Tinjum & Edil, 2016).

The mechanical properties of hydraulically bound mixtures can vary considerably. This is due to the different properties of the components and their proportions. The main factors include the type of soil used, the type and amount of binder, and the curing conditions of the mixes. While the type of soil and binder used is often the subject of research studies, the effect of specimen treatment on their properties, including non-destructive testing results, is less frequently discussed. This paper presents the effect of treatment on ultrasonic pulse velocities.

MATERIAL AND METHODS

In this paper, a study was conducted on cement stabilized soils. The mixture used consists of soil and 3% binder. All samples were compacted at optimum moisture content with an energy of 0.59 $J \cdot m^{-3}$. The samples were formed in two-part cylindrical molds. The produced samples are 8 cm in height and 8 cm in diameter. The manufactured samples were divided into seven groups. Each group consisting of three samples was subjected to different curing. The care period of 28 days includes: Z – days during which the sample is kept in a room with constant temperature and humidity, Q – days during which the samples are immersed in a water tank. A summary of the mixes and their treatments were shown in Table 1.

Table 1. Types of mixes and their treatment

Sample group	Binder [%]	Z days	Q days	$Z + Q$
A	3	28	0	28
B	3	27	1	28
C	3	25	3	28
D	3	21	7	28
E	3	14	14	28
F	3	7	21	28
G	3	1	27	28

The mixtures were made using soil taken from the bottom of the excavation at a depth of 3 m. The basic physical properties have been determined in accordance with the standard EN 1997-2 (European Committee for Standardization [CEN], 2009). All the main information is given in Table 2, and the grain size curve of the soil under study is shown in Figure 1. Soil is classified as clayey sand (clSa) according to the standard EN ISO 14688-2 (International Organization for Standardization [ISO], 2018).

Table 2. Properties of the soil

Physical property	Value	Unit
Plasticity index (*PI*)	10.41	–
Liquidity index (*LI*)	0.31	–
Liquid limit (*LL*)	18	%
Plastic limit (*PL*)	7.59	%
Water content (*W*)	10.8	%
pH	8.95	–
Maximum dry density (*MDD*)	2.08	$g \cdot cm^{-3}$
Optimum moisture content (*OMC*)	8.64	%

Blast furnace cement (BFC) was used to produce the stabilized soil mixtures. It is composed of ordinary Portland cement, blast furnace slag, and other additives. The blast furnace slag content is up to 65% of a mixture (Napp, Gambhir, Hills, Florin & Fennell, 2014). It is a commonly used binder for soil stabilization. Properties of the binder are summarized in Table 3.

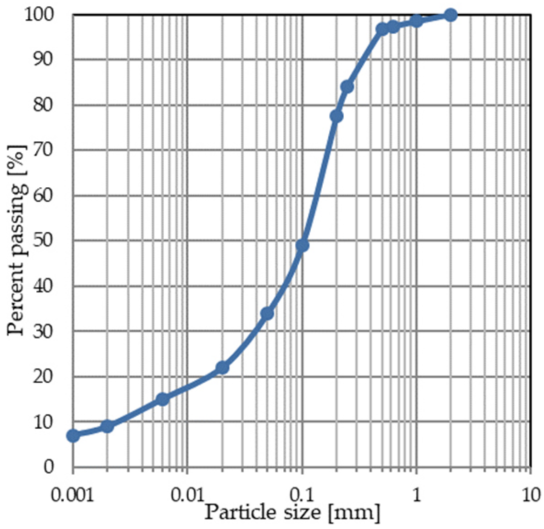

Fig. 1. Grain size distribution curve of soil

Table 3. Properties of the binder

Property	Value	Unit
Binder type	blast furnace cement (BFC)	–
Designation	CEM III/A 32.5N-LH/ /HSR/NA	–
Required compressive strength after 7 days	≥ 16.0	MPa
Required compressive strength after 28 days	≥ 32.5	MPa
	≤ 52.5	MPa
Hydration heat	≤ 270.0	$J \cdot g^{-1}$

After the care period shown in Table 1, ultrasonic pulse velocity (*UPV*) measurements were performed for all sample groups tested. Ultrasonic pulse velocity was measured using a Proceq apparatus. A Pundit Lab Plus device and transducers with a frequency of 54 kHz were used for the research. The instrument was calibrated each time before the measurements using the equipment provided (calibration rod). The instrument needs to be recalibrated after each change of cables or transducer frequencies. In order to correctly measure the wave speed, a gel was applied to the contact surface of the sample and transducers. Specific instrument details are shown in Table 4. Testing was conducted after 28 days of sample treatment. A scheme of the tests performed is presented in Figure 2. The measuring device is shown in Figure 3.

Table 4. Proceq – pundit lab plus parameters

Parameter	Value	Unit
Range	1 000	µs
Resolution	0.1	µs
Frequency used	54	kHz
Pulse width	9.3	µs
Used excitation voltage	250	v
Calibrated time offset	–5.6	µs

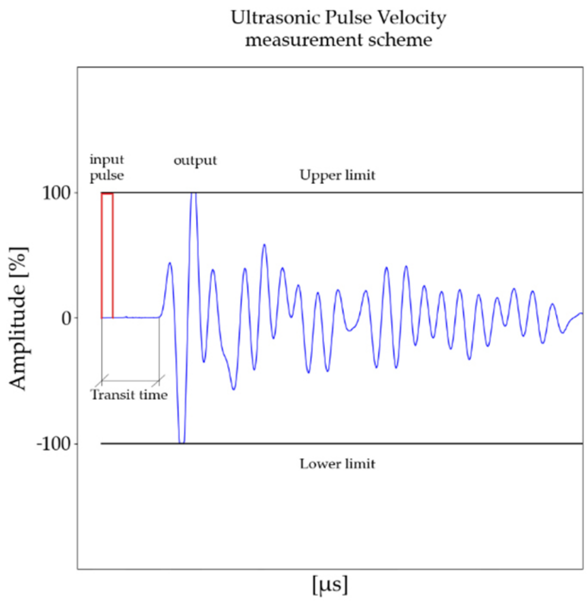

Fig. 2. Ultrasonic pulse velocity test measurement scheme

The time it takes for the wave to travel through the test medium is measured during the test. Then, based on the measured value and the distance between the two transducers, the ultrasonic pulse velocity is determined, which can be represented by the following equation:

$$UPV = \frac{L}{T}$$

where:
UPV – ultrasonic pulse velocity [$m \cdot s^{-1}$],
L – distance between two transducers [m],
T – measured time [s].

Fig. 3. Ultrasonic pulse velocity measuring device: Pundit Lab Plus device, transducers, calibration rot

After the ultrasonic pulse velocity measurements were completed, each sample was weighed. Then the samples were dried in a chamber at a constant temperature of 105°C. After drying, the samples were weighed, and the moisture content of each sample was determined.

RESULTS AND DISCUSSION

This paper contains results from tests on 21 cement--stabilized soil samples. Based on the results obtained, the effect of the duration of immersion of the test mixture samples in the water tank on the ultrasonic pulse velocity was analyzed. In addition, the impact of the length of immersion of the samples in water on the moisture content after 28 days of curing was investigated. Figure 4 presents representative received waves for each tested group.

The influence of the duration of immersion of the specimens in water has a significant effect on the curing effect of the mixture, as shown by the changes in the ultrasonic pulse velocity. The obtained wave speed results are shown in Figure 5.

More than 5% increase in *UPV* can be observed as early as one day's immersion of the specimen in water. The effect intensifies with increasing water

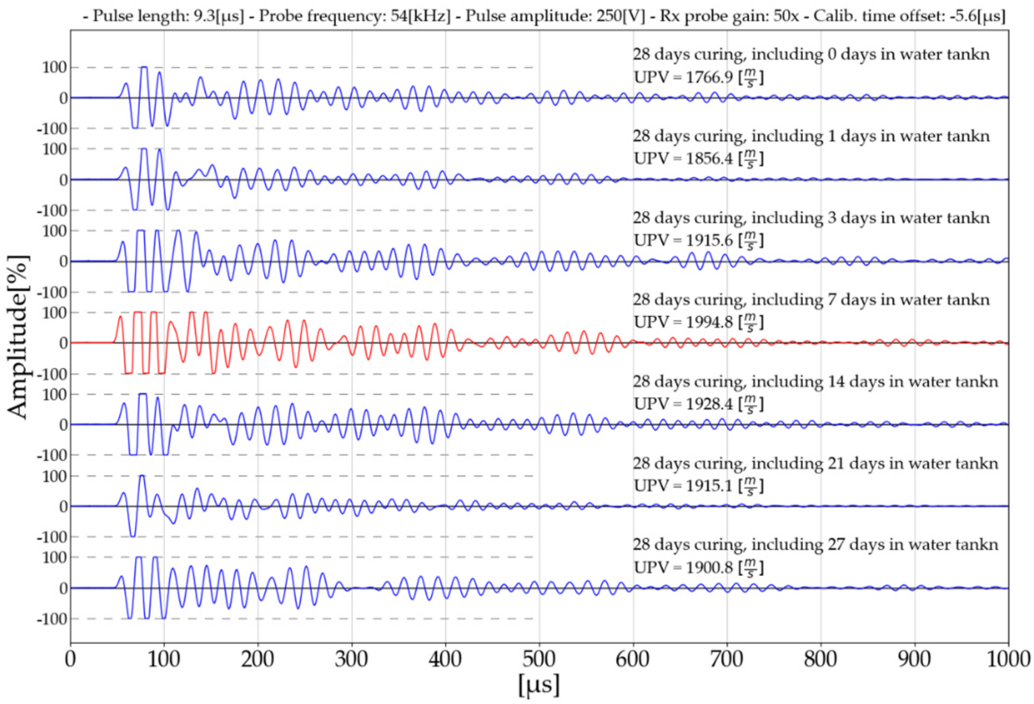

Fig. 4. Received signals for each test group

immersion time. Extreme increases of 12.9% are achieved by Group D, i.e. samples that have been immersed in water for seven days. After this time, each increase in the immersion time of the samples in the water tank causes a gradual decrease in the ultrasonic pulse velocity. However, this decrease is small enough that despite the decreasing trend, the results still obtain higher velocities than the results obtained on samples without a care in the water tank or after one day. The increase in velocity of the ultrasonic pulse in the tested samples is directly related to the saturation of the tested medium with water, which translates into lower energy loss of the transmitted signal during its passage through.

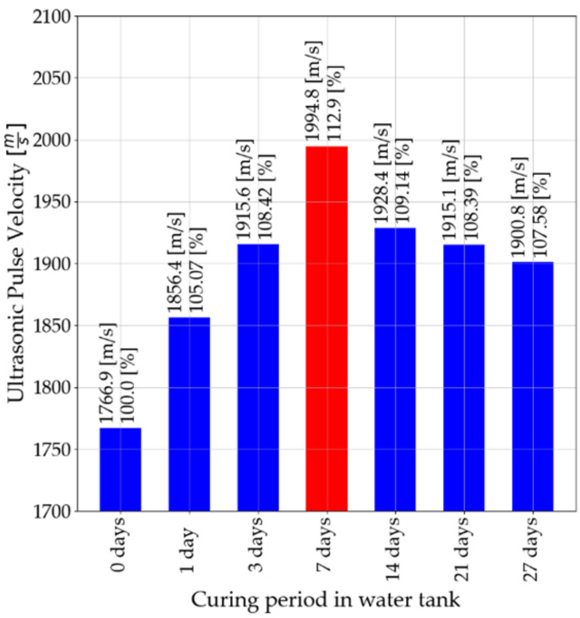

Fig. 5. Summary of ultrasonic pulse velocity test results as dependent on water immersion time

Figure 6 shows the change in moisture content of the different groups of mixtures. A continuous increase in moisture content with increasing time of immersion in water of the tested samples is observed. The highest growths were obtained already after one and then after three days of immersion of the material in water. After the third day, there was a slight increase in moisture content.

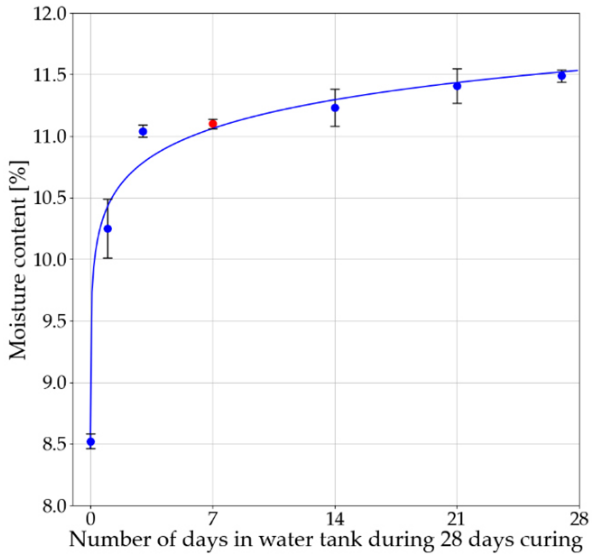

Fig. 6. Change in moisture content of stabilized soil as the number of days in the water tank

CONCLUSIONS

In the existing regulations, it is possible to find different recommendations for treating stabilized soil samples. Therefore, there is a need to know their influence on the obtained results. This paper presents results showing the impact of seven types of care on the results of non-destructive testing and moisture content. Based on the presented results, the most important observations are formulated:

1. In stabilized soils, the highest ultrasonic pulse velocities were obtained for Group D mixtures. This group was treated for 21 days in a constant humidity chamber and seven days immersed in water.
2. The highest increase in sample moisture is achieved during the first three days of immersion in water. The study shows that the highest moisture content was achieved by samples immersed in water for 27 days.

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WPŁYW PROCESU PIELĘGNACJI NA PRĘDKOŚĆ IMPULSU ULTRADŹWIĘKOWEGO W GRUNTACH STABILIZOWANYCH

STRESZCZENIE

Proces pielęgnacji gruntów stabilizowanych spoiwem hydraulicznym ma wpływ na wyniki badań niszczących i nieniszczących. Sam proces jest zależny od kraju wykonywania stabilizacji. W pracy zbadano wpływ długości zanurzenia próbek gruntów stabilizowanych podczas procesu utwardzania na prędkość impulsu ultradźwiękowego. Przeprowadzone badania wykazały wzrost prędkości o 12,9% w próbkach, które poddano siedmiodniowemu zanurzeniu w wodzie. W pracy przedstawiono wyniki dla siedmiu sposobów pielęgnacji.

Słowa kluczowe: prędkość impulsu ultradźwiękowego, grunt stabilizowany, okres pielęgnacji