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EFFECTIVE MECHANICAL PROPERTIES IDENTIFICATION OF THE CONCRETE FROM THE HISTORICAL BRIDGE STRUCTURE

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Abstract. One of the first and most important tasks in a complex and precise assessment of the current condition and load-bearing capacity of existing structures is a determination of the physical and mechanical parameters of the materials used. This problem is even more complicated when a historical concrete structure is assessed. This study shows the possible way how to perform an effective and comprehensive evaluation of the concrete taken from the historical bridge structure with the use of a wide range of non-destructive and destructive methods.

Keywords: Concrete, bridge structure, diagnostics, core drilling, compressive strength, ultrasonic pulse velocity test, resonance method.

1. Introduction

Nowadays, concrete is the most commonly used material in civil engineering, usually in the form of reinforced, or prestressed concrete structures. The main development of concrete with Portland cement and reinforced concrete structures is dated from the second half of the 19th century. Consequently, the first standards and regulations for concrete structures were published [1].

At the beginning of the 20th century on the territory of the Czech Republic, reinforced concrete for structures, especially for bridges, began to be used widely in the construction industry. The quality of the concrete from this time cannot be comparable with modern concrete in general. Poor quality of the cement, unsuitable aggregate (inappropriate aggregate grading, alkali-aggregate reaction), and insufficient methods for concrete compacting during the casting are often characteristics of concrete from this era.

Unknown and non-homogenous quality, deterioration of the concrete, a limited amount of the possible taken samples, etc. are the problems that could negatively affect the resulting characteristics of the tested material. However, if these problems are assumed, there are procedures and methods that can help us with the effective and correct determination of material properties. This paper deals with a complex description of the material properties of concrete samples taken from historical arch bridge structure with the use of a wide range of non-destructive and also destructive methods. The study continues with a complex assessment of the historical reinforced concrete arch bridge. Results obtained from this study will be used as inputs for non-linear finite element method analysis of the bridge. The detailed numerical analysis will supplement the assessment of the structure based on the results gained during the full-scale load test described in [2].

2. Materials and methods

2.1. Considered structure and sampling

The structure determined for evaluation of concrete properties was a historical reinforced concrete arch bridge over the Litava stream in the South Moravian region in the Czech Republic (see Figure 1 top). The bridge was built after World War I, during the 1920s. For over 100 years the bridge did not undergo any specific maintenance or reconstruction, except repairs of the bridge deck after the damage caused at the end of World War II.

Before a sample collection, a detailed visual inspection of the structure was performed. The inspection included the measuring of the main dimensions of the bridge, visual assessment of deterioration and damages of the bridge members, and preliminary localization of the reinforcement bars. Subsequently, the locations for samples collecting with the use of a core-drilling rig were determined. The main requirement for the location of the sampling was the consideration, that concrete at this part is not subjected to tension stresses, and the quantity of the reinforcements allows drilling in between reinforcement bars. The additional requirement was that the diameter of the cores must be at least three times greater than the maximum size of the aggregate used in the concrete [3]. Due to these limitations, samples of a nominal diameter of 100 mm from support cross girders and from the ends of the main arches (see Figure 1 bottom) were collected. Five cores from the support cross girders and two samples from the main arches were collected in total.

2.2. Classification of samples and preparations of tests

Due to minimizing damages to the structure caused by core drilling, a limited number of samples were

FIGURE 1. Arch bridge over Litava stream subjected to assessment (top), collecting of the concrete samples with the use of the core-drilling method (bottom).

FIGURE 2. Core samples prepared for preliminary non-destructive sorting (top), cores divided into test specimens based on the results of non-destructive testing (bottom).

obtained. For the need to characterize concrete as precisely as possible, was decided to use two non-destructive methods to rate the samples by their quality. Firstly, core samples were labeled, visually evaluated, and the ends of the cores were cut off (see Figure 2). For the non-destructive determination of concrete quality combination of the ultrasonic pulse velocity method and resonance method was used. Final sorting was done based on the dynamical properties – the dynamic modulus of elasticity of concrete.

2.2.1. Ultrasonic pulse velocity method

The principle of the ultrasonic pulse velocity method is the transmission of ultrasonic pulses into the tested material and the determination of the transmission time T. Subsequently, the ultrasonic pulse velocity (UPV) through the material v (see Figure 3 top) is determined according to the standard [4]. The dynamic Young's modulus can then be calculated according to standard [5] using the equation:

$$E_{cu} = Dv^2 \frac{(1+\mu)(1-2\mu)}{(1-\mu)}, \tag{1}$$

where E_{cu} is the dynamic modulus of elasticity in MPa, D is the density of the material in $\mathrm{kg\,m^{-3}}$, v is the UPV in $\mathrm{km\,s^{-1}}$ and μ is the Poisson's ratio, which was determined using the resonance method.

A Pundit PL-200 instrument with 150 kHz probes was used to determine the dynamic modulus of elasticity. The UPV was determined in three longitudinal lines on each test specimen. The average value of UPV was used in the calculation of E_{cu} according to Equation 1.

2.2.2. Resonance method

Any object made of solid material vibrates after a mechanical impulse and this vibration can be different. The natural frequencies of longitudinal, flexural, and torsional vibrations of specimens of regular geometric shapes are used to evaluate the dynamic properties of the material [6]. The dynamic Young's modulus can be calculated in accordance with the standard [7] from the natural frequencies using the Equation:

$$E_{crL} = 4L^2 f_L^2 D, \tag{2}$$

where E_{crL} is the dynamic modulus of elasticity in MPa, L is the length of the test specimen in m, f_L is the natural frequency of longitudinal vibration in kHz and D is the density of the material in $\mathrm{kg\,m^{-3}}$. The dynamic Young's modulus can be also calculated from the equation:

$$E_{crf} = 0.0789 c_1 L^4 f_f^2 D i^{-2}, \tag{3}$$

where E_{crf} is the dynamic modulus of elasticity in MPa, c_1 is the correction coefficient depending on the i/L ratio, L is the length of the test specimen in m, f_f is the natural frequency of the flexural vibration in kHz, D is the density of the material in $\mathrm{kg\,m^{-3}}$ and i is the radius of gyration of the test specimen cross-section in m.

Each test specimen of concrete was excited by a mechanical impulse using an impact hammer in accordance with Figure 3 (bottom). The natural frequencies were determined using a Handyscope HS4 oscilloscope

FIGURE 3. Non-destructive evaluation of the concrete samples and specimens. Ultrasonic pulse velocity method (top), resonance frequency method (bottom).

Core Sample	Specimens	Test Method
V1	1.1	Modulus of elasticity – E_c
	1.2	Uniaxial tensile strength – f_t
	1.3	Compressive strength – f_c
V2	2.1	Uniaxial tensile strength – f_t
	2.2	Water absorption – WA
	2.3	Modulus of elasticity – E_c
V3a	3.1	Compressive strength – f_c
	3.2	Compressive strength – f_c
V3b	3.3	Compressive strength – f_c
V4	4.1	Compressive strength – f_c
	4.2	Water absorption – WA
	4.3	Modulus of elasticity – E_c
V5	5.1	Compressive strength – f_c
	5.2	Uniaxial tensile strength – f_t
	5.3	Uniaxial tensile strength – f_t
V6	6.1	Modulus of elasticity – E_c
	6.2	Uniaxial tensile strength – f_t
V7	7.1	Compressive strength – f_c
	7.2	Water absorption – WA
	7.3	Compressive strength – f_c

TABLE 1. Groups of the specimens and test plan.

with an acoustic emission sensor and software (supplied with the oscilloscope) that works based on a fast Fourier transform.

Based on the results of the first assessment, core samples were saw-cut to the test specimens with lengths from 60 to 200 mm. After that, the second non-destructive measure was performed on the adjusted test specimens using the assigned test method for each test specimen. Four specimens for modulus of elasticity tests were cut to the length of 200 mm, i.e., length to diameter ratio equals 2.0. The remaining specimens were divided into two sets to determine the compressive strength and uniaxial tensile strength of the concrete. In each group specimens with various dynamic properties were included. Specimens subjected to these tests have quality corresponding with the overall quality of the concrete samples obtained from the structure. Besides that, three specimens with lengths less than 100 mm were set up for the water absorption of concrete determination. The sorting of the test samples and specimens and the test plan are shown in Table 1.

2.3. Determination of the physical and mechanical properties

After the non-destructive quality identification of the subjected concrete and assorting of the specimens, the determination of the main mechanical, and also physical parameters of the material followed. For the vast majority of analytical, or numerical approaches for the assessment of the load-bearing capacity of the structure, it is important to know as many mechanical material properties of the materials used as possible. In the case of concrete, the basic strength parameters are the compressive and tensile strength of the concrete. Apart from the strength parameters, materials are also described in the form of the deformation parameters of the material. Usually, the parameter is expressed by Young's modulus – in other words, the modulus of elasticity. In this study, the mentioned mechanical parameters of the concrete were primarily evaluated. In some cases, in addition to these main mechanical parameters, the fracture energy of the concrete can be also determined. This parameter is greatly important in the case of non-linear analysis of the structure. However, in this specific study, the fracture energy of the concrete was not determined due to the limited quantity of samples. Also, the basic physical properties like the volume density of all specimens and water absorption were determined.

2.3.1. Compressive and uniaxial tensile strength

Undoubtedly, one of the basic and the most frequently executed tests of hardened concrete is the compressive strength test. In this case, compressive strength was determined on the specimens with a diameter and length of 100 mm (length to diameter ratio equals 1:1). The test follows the instructions in the European standard for hardened concrete testing [8]. Assessment of the compressive strength of the concrete is supplemented by characteristic compressive strength value determination and strength grade classification using the approaches given in the [9, 10] and in an invalid standard: Designing of concrete structures, used in the era of the 30th years of 20th century [11].

The uniaxial tensile strength test is not often performed type of the test to determine the tensile strength of concrete. In most cases are tensile strength values based on results from splitting or four-point bending tests. These tests are less time-consuming in terms of preparation of the experiment than the uniaxial test. Also, in the case of the four-point bending test, there is the possibility to use halves later for the splitting test, hence three values of tensile strength from a single test specimen are obtained. Czech standard [12] covers the requirements and process of the uniaxial tensile testing. In this study, the test was supplemented by measurements of the strain during the testing (see Figure 4). For this purpose, two longer specimens which were determined to uniaxial strength test were fitted with a pair of strain gauges. Values of the strain gained during the test were used for the determination stress-strain curve of tested concrete under the tensile load later on.

Figure 4. Compressive strength test (top), uniaxial tensile strength test with measurement of strain during the test (bottom).

2.3.2. Static modulus of elasticity

In the case of detailed analysis of the structure, in terms of deformations analysis or NLFEA, the modulus of elasticity is a more important parameter than the strength of the material. This constant describes the deformation behaviour of the material during the loading. Especially, values of modulus of elasticity for concrete can vary from 10.0 to 35.0 GPa. In the standards and recommendations (for example American [13], or European [14]) formulas for the calculation of modulus of elasticity based on the compressive strength of concrete can be found. This approach can be used only for modern and ordinary concrete. The modulus of elasticity gained from this method has only approximate character and often the real values can differ by tens of percent against reality. For that reason, the best approach to determine the modulus of elasticity is by experiment. In this study, the modulus of elasticity was determined following [15]. During the tests, the strain was measured with two separate methods: commonly used strain gauge extensometer and bonded foil strain gauges (see Figure 5). Extensometer was attached to the specimens only during the cyclic loading, whereas the bonded strain gauges were used for continuous measurement until the failure of the test specimens. The standard time course of the test consists of cyclic loading between 0.5 MPa and one-third of the compressive strength of concrete. The test contained two preliminary cycles and the third measured cycle. Each specimen was then continuously loaded until failure occurred. Strain measured with the use of embedded strain gauges was used for the determination of the stress-strain curve for this particular concrete subjected to compression loading.

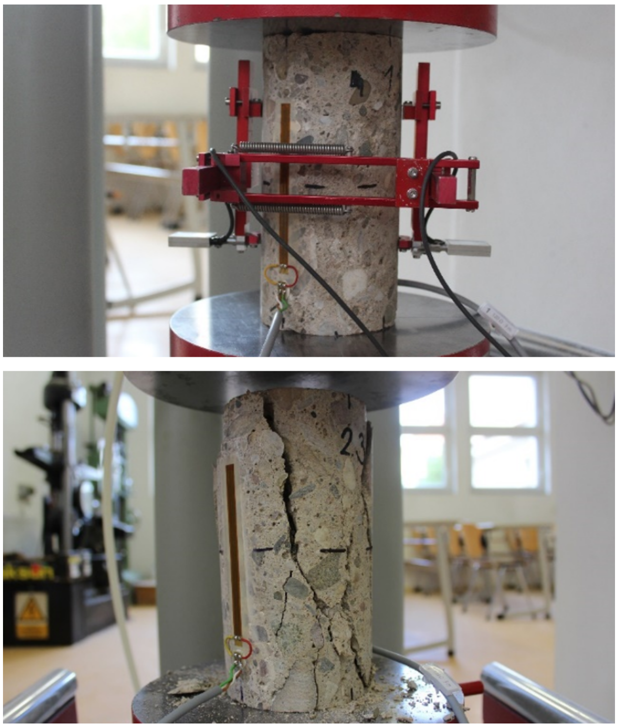

Figure 5. Test specimen during cyclic loading with strain gauges and extensometer (top), test specimen after failure (bottom).

3. Results

Corresponding to the study, firstly the results of the non-destructive analysis of concrete are presented. Figure 6 shows values of the dynamic properties of the whole core samples, and also properties determined on the adjusted test specimens. Assessment of the samples and cores was based on the values of dynamic

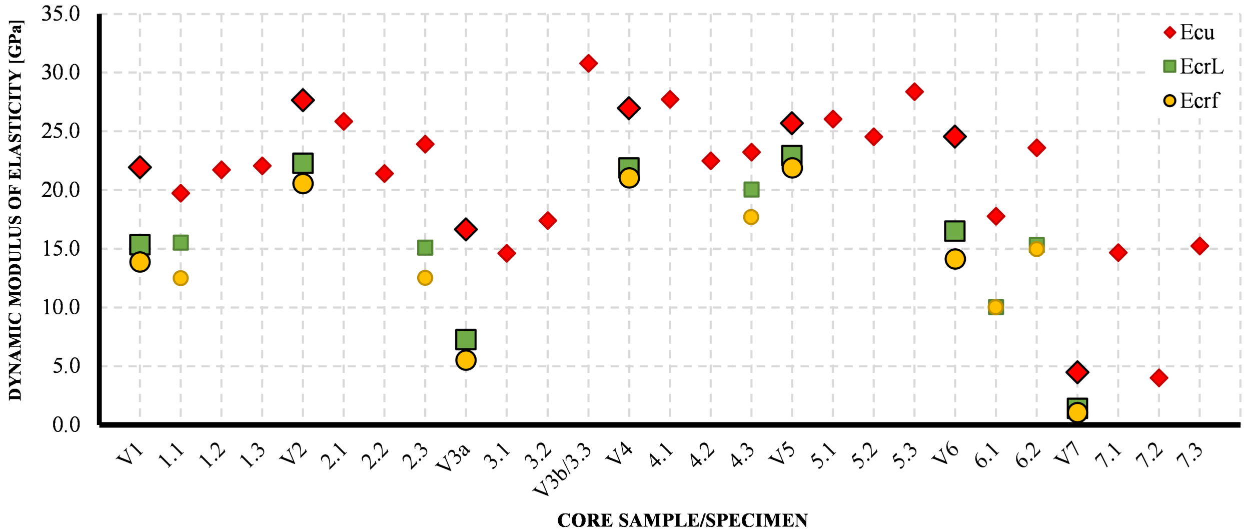

FIGURE 6. Results of the dynamic modulus of elasticity based on parameters measured with the use of the UPV method and resonance method determined on both core samples and adjusted specimens.

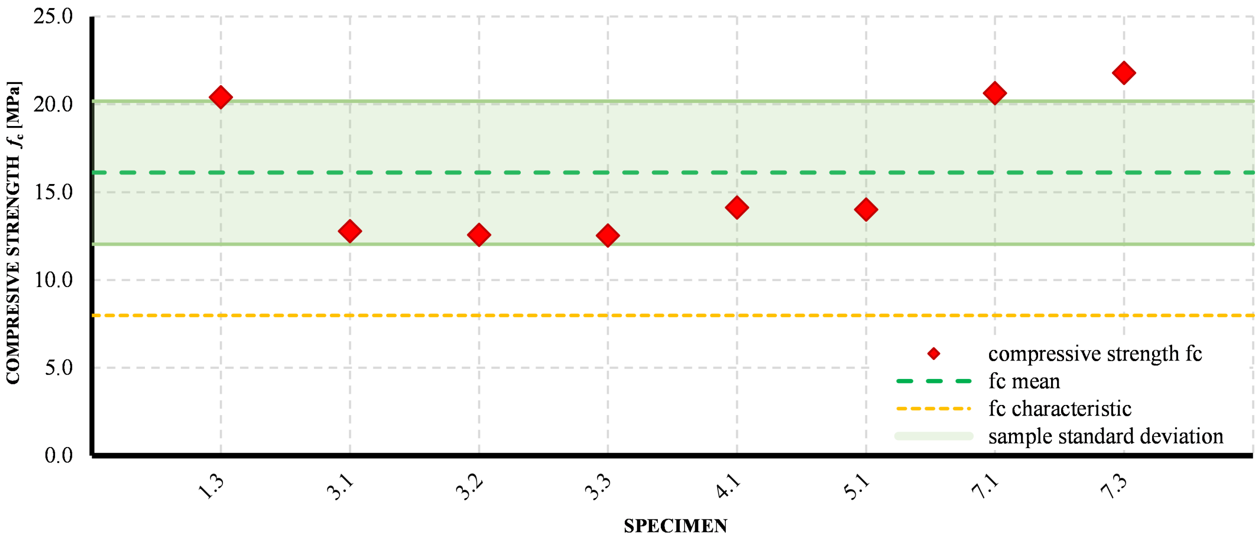

FIGURE 7. Results of the compressive strength tests.

modulus of elasticity gained using the UPV method – E_{cu}. In the case of the resonance method, the evaluation of the samples and specimens was performed based only on the measurement of longitudinal and flexural frequencies, hence shear modulus of elasticity (from the torsional frequency) was not used. In addition to this, results gained from resonance frequency modulus (E_{crL} and E_{crf}) are presented. It can be seen, that except for samples V3a and V7 results of the dynamic properties are consistent, also the difference between the dynamic modulus of elasticity E_{crL} and E_{crf} are negligible. Some of the results based on the measurement of saw-cutted specimens show slight deviations in the dynamic properties from the results of the whole test sample. These deviations can be caused for example by large aggregate grains presence, or the local poor quality of the concrete matrix. In the case of sample V3b and specimens with a length of 100 mm, the resonant frequency measurement cannot be performed due to an unsuitable length-to-diameter ratio.

Figure 7 describes the results of the compressive strength tests performed on the specimens with length to diameter 1:1, thus cube compressive strength values are assessed. Specimens that were made from core samples V1 and V7 had slightly higher compressive strength than the rest of the specimens. This effect could be observed due to the shape or size of the aggregate in the specific test specimen.

Table 2 summarizes the overall compressive strength values, moreover, concrete grade according to [10] is assessed. In this case, tested concrete does not fulfil requirements for the existing lowest concrete grade C 8/10, for this reason, this particular concrete was classified as concrete of non-existing grade (C 6/7.5). This assessment was supplemented by grading concrete using standards for the designing of the concrete structures used in the 1930s [11] when the bridge was

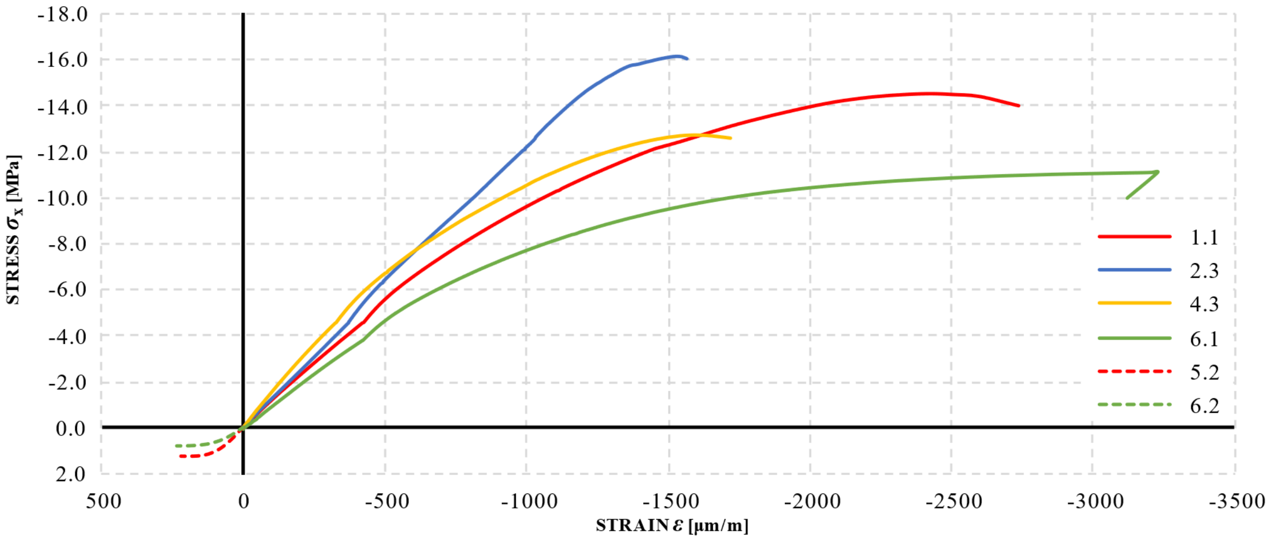

Figure 8. Stress-strain diagrams of tested concrete.

built. Thus, based on this standard tested concrete meets the requirements for the concrete class named d. The main requirement for this concrete class is that the minimal concrete cube strength must be higher than 12.5 MPa.

Mean f_c [MPa]	16.1
Sample standard deviation (SSD) [MPa]	4.1
Minimal compressive strength $f_{c,min}$ [MPa]	12.5
Characteristic compressive strength f_{ck} [MPa]	8.0
Concrete grade [EN 206+A2] [10]	(C 6/7.5)
Concrete class [ČSN 1090:1931] [11]	d

Table 2. Compressive strength results.

Values of the tensile strength are shown in Table 3, except for the tensile strength of specimen 1.2 the results are consistent. A significantly lower value of the strength of the mentioned specimens was induced by poor cohesion between the cement matrix and large aggregate grains and the unsuitable shape of the aggregate of this particular test specimen but the observed failure mode was correct.

Specimen	**Uniaxial Tensile Strength [MPa]**
1.2	0.38
2.1	1.16
5.2	1.19
5.3	1.24
6.2	1.19
Mean f_t [MPa]	**0.95**
Sample standard deviation [MPa]	0.37

Table 3. Uniaxial tensile strength results.

Evaluated data (see Table 4) gained during static modulus of elasticity tests shows a mean value of 13.0 GPa, the difference between E_c values based on the different measurement techniques of deformations is 4.5 %. These differences are negligible, and they are caused primarily by the different locations of the measurement gauges on the specimens. However, overall values of the static modulus of elasticity are consistent and correspond to the quality and composition of concrete.

Stress-strain diagrams gained out of the uniaxial tensile and compressive tests are shown in Figure 8. Diagrams represent a relationship between deformation and stress during the loading of the specimens. As was mentioned before, the strain was measured with the use of foil strain gauges bonded on the specimen's surface. The slope of the initial linear part of the compression and also the tension part of the diagram corresponds to the values of the modulus of elasticity. This linearity is observed until approximately 1/3 of the ultimate compressive load is reached. The maximal measured strain when the failure occurred was within a range of 1 500 to 2 500 μm m^{-1} in case of compressive stress and 20 μm m^{-1} in case of tensile loading.

Specimen	**Modulus of Elasticity E_c [GPa]**	
	Extensometer	**Foil Strain Gauges**
1.1	14.8	12.1
2.3	13.5	13.9
4.3	13.7	14.7
6.1	11.0	10.1
Mean E_c [GPa]	13.3	12.7
Sample standard deviation [GPa]	1.6	2.0
Overall Mean E_c [GPa]	**13.0**	
Overall SSD [GPa]	1.7	

Table 4. Modulus of elasticity results.

Last but not least, the volume density of the concrete was determined. Figure 9 represents values of volume density determined on the adjusted test specimens before testing. Tested concrete had an average volume density of 2 190 kg m^{-3} with a sample standard deviation of 41.5 kg m^{-3}. Also, water absorption of 6.6 % on samples 2.2, 4.2, and 7.2 was determined. Results of similar studies can be found in [16] or [17].

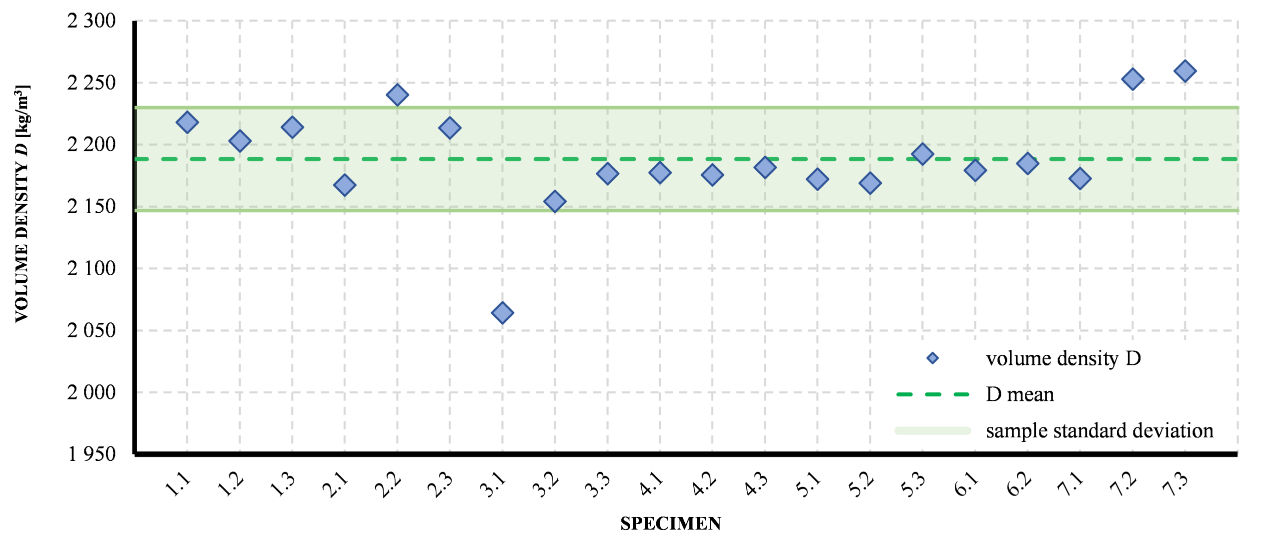

Figure 9. Results of the volume density of concrete determined on the test specimens.

4. Conclusion

A comprehensive determination of the concrete properties taken from more than 100 years old historical reinforced bridge structures within a detailed assessment of the current condition of the bridge was described. The paper covers the process of effective and detailed determination of material properties of concrete, with the use of the combination of non-destructive and destructive test methods in general. The main mechanical and physical properties of the concrete were determined. In the case of this specific study, the assessment of the concrete was divided into two main steps. Firstly, non-destructive measuring was performed. Based on the results of the evaluated ultrasonic and resonance measurement, the core samples were divided into groups of test specimens for the particular test method. Subsequently, the main destructive tests were executed and evaluated. From the results, it can be seen that preliminary non-destructive evaluation of the test samples is important, especially when a limited amount of test samples is available. The non-destructive methods can significantly help with revealing damages and defects of the internal structure of the concrete before the performing of the destructive test methods. The results obtained from this study will be used as inputs for the numerical model of the bridge for the further assessment of the structure behavior under various types of loading conditions.

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