APARATURA
BADAWCZA I DYDAKTYCZNA

The use of a concrete testing machine as teaching equipment in engineering education

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ABSTRACT/SUMMARY:

The paper describes how a materials testing machine can be used during laboratory classes to evaluate the properties of concrete and to demonstrate destructive testing techniques. The lab classes are designed to help students understand the concepts and determination methods for random dispersion, stress-strain and force-strain relationships, ultimate strain and concrete quality through the comparison of the results to the requirements set forth in Eurocode 2.

The machine is used to test the compressive strength of concrete and the modulus of elasticity of concrete, including high-strength concrete. The testing system offers electronic measurement and simultaneous registration of the basic test parameters (destructive force, strain – also for individual load levels, modulus of elasticity of the test specimen, duration of the test, etc.), graphical representation of quantities and statistical calculations for the test specimens. The parameters measured during the test allow the evaluation of concrete class in the tested specimens and the quality control of a given batch of concrete, important for the safety of the structure and its serviceability.

Zastosowanie maszyny wytrzymałościowej do badania właściwości betonu w dydaktyce

Słowa kluczowe: maszyna wytrzymałościowa, beton, wytrzymałość na ściskanie, moduł sprężystości, badania niszczące, zajęcia laboratoryjne

STRESZCZENIE:

W artykule przedstawiono zastosowanie maszyny wytrzymałościowej w celu zilustrowania właściwości betonu i metod realizacji badań niszczących podczas zajęć laboratoryjnych, pod kątem wykazania losowego rozrzutu wyników, oceny zależności siła-odkształcenie, naprężenie-odkształcenie, odkształcenia granicznego, jakości betonu i porównania wyników z normą EC2.
Maszyna wytrzymałościowa daje możliwość przeprowadzenia m.in. badania wytrzymałości betonu na ściskanie, jak również badania modułu sprężystości betonu, w tym betonów wysokiej wytrzymałości. Zestaw badawczy umożliwia elektroniczną formę jednoczesnego pomiaru i zapisu podstawowych parametrów danego badania (siły niszczącej, odkształceń – również dla poszczególnych poziomów obciążenia, modułu sprężystości badanej próby, czasu trwania badania itp.), generowanie podczas badania wykresów zależności żądanych wielkości, a także dokonanie obliczeń statystycznych dla badanych elementów. Mierzone podczas badania wielkości parametrów pozwalają m.in. na dokonanie oszacowania klasy betonu badanych prób, modułu sprężystości oraz jakości produkcji danej partii betonu, ważnej dla bezpieczeństwa konstrukcji i jej użytkowania.

1. INTRODUCTION

In today's fast-paced construction industry, the assessment of the quality and durability of the materials used for the construction of engineering structures or buildings is an important factor in establishing structural safety. The structure should be designed so that compliance with the requirements for strength, stability and serviceability at service loads does not generate excessive unforeseen maintenance costs [1]. The mechanical and physical properties of structural concrete should not reduce the capacity of the structure or affect its performance under given conditions [2]. Insufficient quality of the building materials offered by business operators is one of many causes of malfunctions, failure and building disasters. In this regard, the characterization of concrete strength with attention drawn to quality control is an important element in the teaching process.
This article discusses the interpretation of the results of selected properties of concrete, such as compressive strength and modulus of elasticity, obtained from the materials testing machine during laboratory classes.

2. DESCRIPTION OF THE TESTING SYSTEM

The testing machine is an example of equipment used to test the properties of concrete under laboratory conditions. The measuring system of the tester [3] includes the load frame, a hydraulic station, measurement and control system electronics. The load frame consists of the lower crosshead, guide columns and the upper crosshead. The compression platens are attached to the test cylinder piston and the upper crosshead. The upper compression platen, according to [4, 5], is connected by a ball joint for the angular position up to 3°. The maximum compression test force is 6000 kN, thus making it possible to carry out high strength concrete tests. The compression force is measured electronically through a liquid pressure sensor. The view of the load frame with the test specimen is shown in Figure 1.

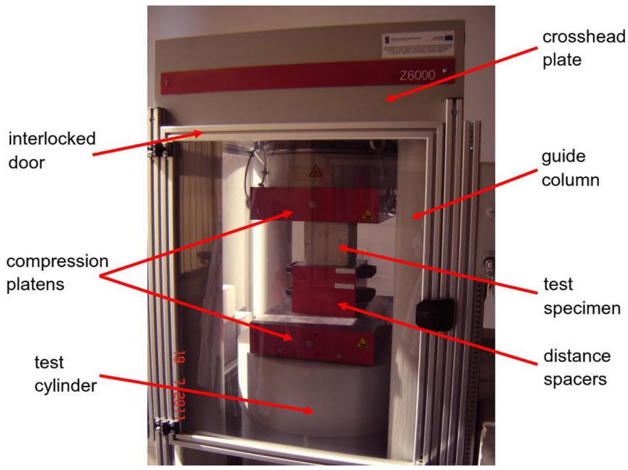

Figure 1 Load frame of the testing machine

The test software, which controls the machine, allows saving test parameters, generating graphs of relationships between quantities and performing statistical computations for the test series.

3. COMPRESSIVE STRENGTH OF CONCRETE – THE EVALUATION OF STATISTICAL AND STRENGTH PARAMETERS

The strength of concrete may vary depending on the aggregate moisture content, cement freshness and quality or concrete mix compaction methods. Therefore, the average value of the compressive strength is a satisfactory parameter for determining the safety of concrete structures. During the classes, the compressive strength values were determined and used to verify the obtained concrete class of two batches of concrete against the design class of concrete, C20/25. The compressive strength tests were performed according to [6, 7] on two series of concrete cubes of side 150 mm, with seven specimens in each series. All the specimens were loaded continuously to the highest load [8]. After the test, the force that corresponds to the maximum force in the compression test was recorded electronically. Table 1 summarizes the laboratory-based measurements of destructive forces and deformations induced by those forces.

Table 1 Destructive force and strain measurements, A) batch S1, B) batch S2

A)

S1 Nr	Specimens name	Maximum force F_{max} kN	Maximum stress MPa	Strain at F_{max} %
1.1	S1 - K1	609.20	27.08	0.67
1.2	S1 - K2	688.12	30.58	0.45
1.3	S1 - K3	692.13	30.76	0.49
1.4	S1 - K4	672.84	29.90	0.55
1.5	S1 - K5	718.42	31.93	0.46
1.6	S1 - K6	682.84	30.35	0.58
1.7	S1 - K7	669.03	29.73	0.45

B)

S2 Nr	Specimens name	Maximum force F_{max} kN	Maximum stress MPa	Strain at F_{max} %
2.1	S2 - K1	596.03	26.49	0.75
2.2	S2 - K2	757.88	33.68	0.70
2.3	S2 - K3	766.61	34.07	0.56
2.4	S2 - K4	761.66	33.85	0.64
2.5	S2 - K5	719.76	31.99	0.70
2.6	S2 - K6	734.74	32.66	0.62
2.7	S2 - K7	738.04	32.80	0.58

The values of ultimate strain were within the range of 0.45% to 0.67% and of 0.58% to 0.75% respectively, thus exceeding the values specified in [1], where ε_{cu} = 0.35%. This shows that the standard referred to in [1] provides safe values. The software package of the machine calculated statistical values such as the mean value $\overline{X}$, the standard deviation s and the coefficient of variation ν of the destructive forces, needed to assess the concrete class and quality. The statistical values for both batches are summarized in Table 2.

Table 2 Statistical values for A) batch S1, B) batch S2

A)

S1 n = 7	Maximum force F_{max} kN	Maximum stress MPa	Strain at F_{max} %
$\overline{x}$	676.1	30.05	0.52
s	33.60	1.49	0.08
ν	4.97	4.97	16.28

B)

S2 n = 7	Maximum force F_{max} kN	Maximum stress MPa	Strain at F_{max} %
$\overline{x}$	725.0	32.22	0.65
s	59.28	2.63	0.07
ν	8.18	8.18	10.67

In order to estimate the class of concrete used in the tested specimens, the average compressive strength f_{cm} was determined as the arithmetic average of individual compressive strength test results. On this basis, the concrete strength class was found to be C16/20 in both series, thereby lower than the design class. After reading the coefficient of variation as a ratio of the standard deviation estimates to the mean, the quality of the tested concrete was found to be very good in S1 specimens and good in S2 specimens. The coefficient of variation did not exceed 7% (ν = 4.97%) and 10% (ν = 8.18%) respectively, as specified in [9].

The software package of the testing machine represents the results in the graphical form for better understanding. Therefore, the force-strain curves were produced for each specimen in series S1. A graph of this relationship is shown in Figure 2.

Concrete is a brittle construction material, in which at low stresses irreversible strain is observed. The plot of force – strain curve, which is nonlinear, is closely related to changes in the structure of the loaded concrete. These changes are triggered by microcracks that form when loading the specimen. Due to the heterogeneous structure of concrete, their growth depends largely on the composition of the concrete mix and the technique of its preparation, which is closely related to the random variation in grain arrangement or adhesion of the aggregate grain surface to the cement paste. Therefore, different plots of force-strain curves are observed in Figure 2, when loading cube specimens obtained from the same batch.

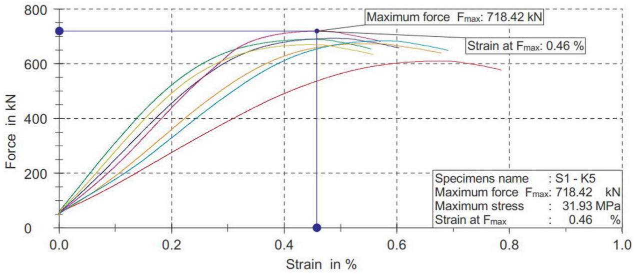

Figure 2 Force – strain relation for each specimen in S1

4. MODULUS OF ELASTICITY

The elastic modulus of concrete is determined within the elastic range by applying stresses from 0 MPa to 0.4 f_{cm}, where f_{cm} is the mean compressive strength of a concrete cylinder [1, 10]. During the cyclic loading in the prescribed range, the secant modulus of elasticity E_{cm} is determined. According to [1], the upper stress value is an approximation. The modulus of elasticity of concrete is the tangent of the slope of a secant to the stress--strain curve. The number of load cycles is not specified in the standards. The modulus of elasticity depends on the composition of concrete, in particular on the aggregate type. The secant modulus of concrete E_{cm} for quartzite aggregates is given in [1, 10]. For limestone and sandstone aggregates the value should be reduced by 10% and 30% respectively. For basalt aggregates the value should be increased by 20%.

5. DESCRIPTION OF THE MEASUREMENT SYSTEM FOR DETERMINING THE MODULUS OF ELASTICITY OF CONCRETE

The modulus of longitudinal elasticity of concrete can be determined in the laboratory using the described machine. The test consists in measuring the linear deformation of the concrete using extensometers. Three cylindrical specimens or four prisms are used. The base of the extensometer is a measuring base, at one end there is a blade, and at the other end a measuring sensor with a blade is mounted. In the middle part of the base there is a magnet, which is attracted by metal discs glued to the concrete. Figure 3 shows the extensometer after all components have been assembled.

Extensometers are manually applied to the concrete specimen so that the sensors are in direct contact [11]. During the loading and unloading cycles, only the transducer is displaced, its linear motion is converted into an electrical signal and measured [12]. The system measures stress and deformation at a fixed concrete compression rate and the changes are recorded by software.

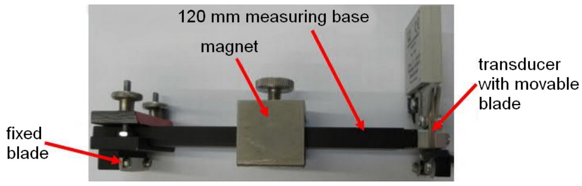

Figure 3 Extensometer for determining the modulus of elasticity of concrete

6. THE ELASTIC MODULUS TEST

The modulus of longitudinal elasticity of concrete was determined during laboratory classes. The aim was to verify the values obtained in comparison with Eurocode 2. The subject of the study were two concrete classes, C40/50 and C25/30. Crushed basalt and limestone aggregates with a maximum grain size of up to 16 mm were used for the production of concrete mix with Portland cement CEM I 42.5. The concrete modulus testing was carried out on cylinders with a diameter of 150 mm and a height of 300 mm, three specimens for a given class. The average concrete strength for classes C40/50 and C25/30 was f_{cm} = 43.35 MPa and f_{cm} = 30.82 MPa respectively. The elastic modulus was determined at two load levels: the constant lower level of 2 MPa and the upper variable level of ≈16.70 MPa for C40/50 and ≈11.50 MPa for C25/30. Three extensometers were attached to the concrete specimens using magnets spaced apart by angle 120°, Figure 4.

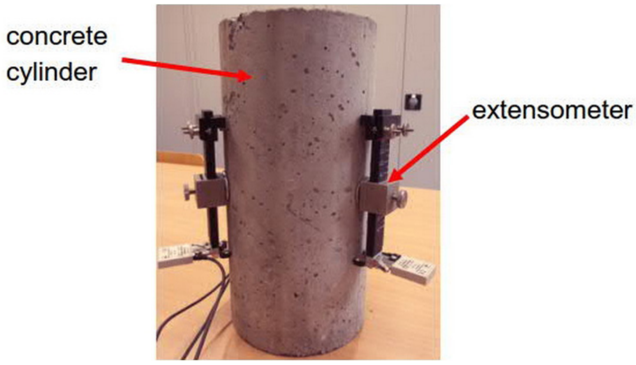

Figure 4 Extensometers mounted on the concrete cylinder

During the test, five calibration cycles and one measurement cycle were carried out. The loading and unloading cycles were continuous at a rate of 0.2 MPa/s. The software automatically created the stress-strain diagram. Upon completion of the test, the software provided statistical values, the average secant modulus of elasticity and the average concrete strain at the upper and lower load level. For didactic purposes, two visualizations of the results were prepared. The first visualization showed all six cycles (Fig. 5) and the second featured only the final measurement cycle (Fig. 6) for three specimens.

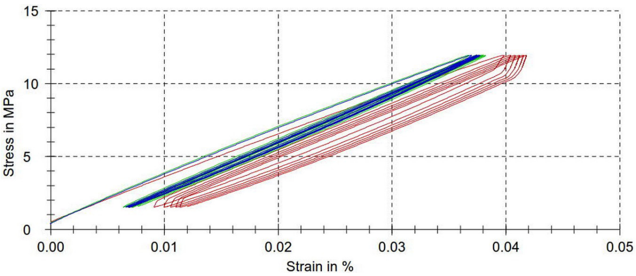

Figure 5 Stress – strain relation for C25/30 concrete – six cycles for three specimens

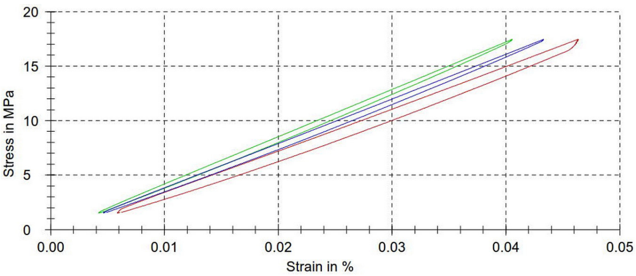

Figure 6 Stress – strain relation for C40/50 concrete – the final measurement cycle for three specimens

The machine performs and displays any number of load cycles, Figure 5. However, considering the purpose of the laboratory classes and for better legibility of the results, the calibration cycles were omitted and only the last measurement cycle was shown, Figure 6. Due to the difficulty in interpreting all the data, Figures 5 and 6, it is appropriate to compare the graphs only for one specimen from each batch (Fig. 7 and 8).

Figure 7 shows the five calibration cycles and the final measurement cycle. The secant modulus for C25/30 concrete was 33.44 GPa. The average strain at the lower-level load was 0.0085%, but at the upper level load it was 0.0369%. The secant line was marked for the sixth load cycle i.e. for the measurement cycle.

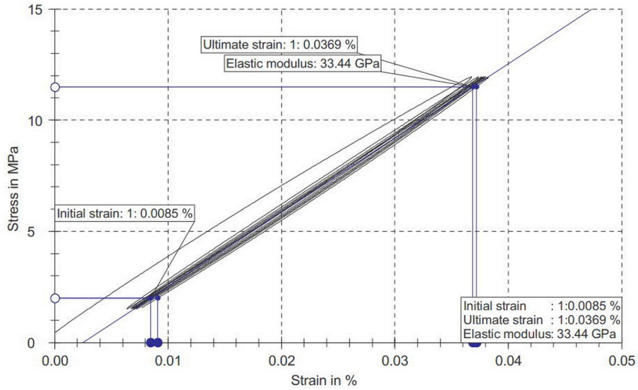

Figure 7 Stress – strain relation and marking the secant modulus of elasticity for C25/30 concrete specimen

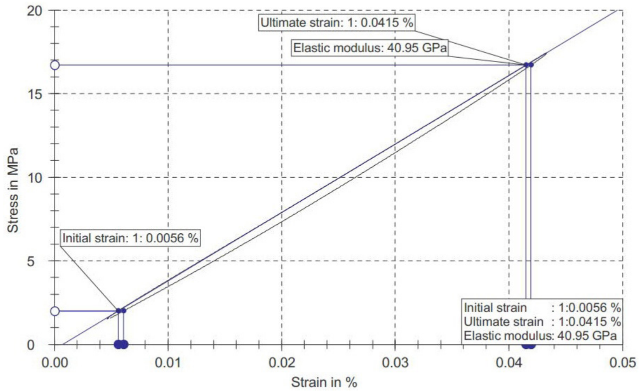

Figure 8 Stress – strain relation and marking the secant modulus of elasticity for C40/50 concrete sample

Figure 8 shows only the measurement cycle. In this case the secant modulus for C40/50 concrete was 40.95 GPa. The average strain at the lower-level load was 0.0056%, but at the upper-level load it was 0.0415%. The secant line, as in the previous case, was marked for the sixth load cycle.

Figures 7 and 8 show that the stress – strain curve has a greater angle of inclination for concrete C40/50 than for C25/30. Similarly, after concrete deformation the strain for C40/50 is above 0.04% but for C25/30 it is below 0.04%. The cause of these changes is the value of the upper load level in the measurement cycle. Thus, the greater the load level of concrete in the cycle, the greater its deformation. The data obtained from the tests included elastic modulus values, Table 3, corresponding plots, Figures 5 and 6, and statistical parameters such as the mean value $\overline{X}$, the standard deviation s and the coefficient of variation ν, Table 4.

Table 3 Elastic modulus results for concrete, A) class C25/30, B) class C40/50

A)

Nr	Elastic modulus GPa
1	33.06
2	33.44
3	33.71

B)

Nr	Elastic modulus GPa
1	38.73
2	43.58
3	40.95

Table 4 Statistical analysis for concrete, A) class C25/30, B) class C40/50

A)

Series n = 3	Elastic modulus GPa
$\overline{x}$	33.40
s	0.33
ν	0.98

B)

Series n = 3	Elastic modulus GPa
$\overline{x}$	41.09
s	2.43
ν	5.91

The analysis so far indicates that the concrete produced with basalt aggregate has a higher average modulus of elasticity than the concrete containing limestone aggregate, the difference being 7.70 GPa. The coefficient of variation values show that C25/30 concrete (ν = 1%) is of very good quality, and the dispersion of the results oscillates around the mean, unlike that of C40/50 (ν = 6%). Experimental values of the elastic modulus after increasing by 20% (for basalt aggregate) and reducing by 10% (for limestone aggregate) are higher than those given in the standard [1]. This is due to the fact that the standard formulas estimate the modulus of elasticity, whereas the experimental study investigates particular material and the results can be subjected to the probabilistic analysis. The higher value of the modulus of elasticity is attributed primarily to the high strength of aggregates (basalt) and to the quality of the concrete.

7. SUMMARY

The testing machine with attached instrumentation, described in this article, can be used to tests the properties of concrete, including high strength concrete, both in research and teaching laboratories. The included software generates graphical representation of the results and facilitates their interpretation. Thus illustrated relationships, trends and statistics provide the best way to learn and understand the mechanical properties of concrete.
As the result of this study, the concrete strength class was found to be lower than the design class, and the plots of force – strain curves provided information about the random variation in the production of concrete. It was also demonstrated that the strength of aggregate affects the determination of the elastic modulus of concrete. Moreover, the load level in the cycle is directly proportional to the deformation of concrete. The obtained experimental values of ultimate strain for concrete under compression and elastic modulus of concrete were higher than those required by [1], which indicates the safe estimation of standard values.

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