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CONCRETE MIX DESIGN USING ABRAMS AND BOLOMEY METHODS

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1. INTRODUCTION

Environmental protection should be a priority in scientific research. This is especially important for the field of concrete technology due to the repercussions of environmental pollution as a result of CO_2 emissions during cement production. If the production of one ton of cement causes the emission of 600 kg of CO_2 and the construction industry is responsible for 8% of total CO_2 emissions it belongs to look for optimal solutions in the production of cement but also in the design of concrete. Scientifics have already taken up this challenge in concrete technology and the results of the research are known, among others (Radhakrishna et al., 2020, Wang et al., 2018, Brito et al., 2018, Chidiac et al., 2013, Popowics, 1998, Popowics, 1985).

The first methods of concrete design were the Abrams and Bolomey methods (Bulletin, 1924, Bolomey, 1935, Karni, 1974,Popovic et al., 1981, Kasperkiewicz, 1994). As these methods are quite simple, they are still frequently used mainly in Europe (Abdelgader et al., 2020, Mishra et. al., 2012, Brandt, 2009, Popovics and Ujhelvi, 2008, Ekinci et. al., 2006, Larrard, 1999). Based on Bolomey's and Abrams' formulas, many computer programs supporting concrete design were created. Attempts were made fiew to modify these methods and the research results were presented in the works (Wang et. al., 2018, Abdelgader et. al., 2013, Abdelgader et. al., 2012, Nataraja et. al., 2012, Ramajane et. al., 2012, Brandt, 2009).

Wang *et al*., 2018 noticed that a concrete mixture with an optimum proportion of fine and coarse aggregates guarantees high strength of concrete. The authors used the Bolomey method to design concrete taking into account the appropriate regulations and grading requirements of the aggregates in the China standards. After concrete test verification, the conclusion was made that with the optimal combination of fine and coarse aggregates, concrete mix proportion is easy to determine. In addition, the authors, based on the research, noticed that the obtained compressive strength was higher by 20% than the designed one. It was assumed that this may be a guarantee of high quality and durability of concrete.

Abdelgader *at el.*, 2013, 2012 in their research took into account the fact that the properties of fresh mix and hardened concrete are significantly related to their composition. The authors referred to other concrete composition design methods such as ACI and BS methods are the most commonly used. The presented research used the modified Bolomey method as The Three Equations Method, which was illustrated in this paper, in addition to the assessment of the laboratory results of concrete mixes produced by this method.

Nataraja and Sanjay, 2012 were dealing with the development of design concrete with Bolomey and Abrams. This research used the impact of aggregate quality on concrete compressive strength. Was researched to proportion mortar strengths to concrete compressive strength and to impact abrasion resistance of the aggregate on the compressive strength of concrete. The research used soapstone as well as granite stone as coarse aggregates. Based on the results, correction to the published modified Bolomey equation is also suggested which can be used for the design of concrete containing soapstone.

Rajamane *at el.*, 2012 used the Bolomey equation has been used for relating the cement–water ratio to the compressive strengths of concrete containing normal and lightweight aggregate (LWA). It was found that this is basically a linear equation, not considering explicitly the parameters relating to coarse aggregates. It has been shown the strengths of lightweight concrete (LWC) containing LWA are influenced both by w/c ratio and the properties of the LWA. A modified Bolomey method, considering indirectly the presence of LWA, is suggested, using the experimental data.

Brandt, 2009 in the book presented a modified Bolomey method for the practical prediction of compressive strength at the age of 28 days. He assumed that compressive strength is mainly on one parameter: this is the water/cement ratio. Traditional formulae described by Bolomey described were have been transformed on the Three Equations method.

In this paper, the authors presented the results of laboratory tests, comparing both methods of concrete design, including the modified Bolomey method. Concrete with assumed compressive strength 25, 30, 35, 40, and 45 MPa was researched. The compositions of concretes were compared and calculated according to two methods. The research was conducted in the laboratory using two types of samples: cubic 15x15x15cm for compressive strength tests and cylinders ϕ-

15cm, h-30cm for the splitting strength tests using the Brazilian method. The obtained test results can be the basis for future modifications of the concrete design methods, taking into account additives and admixtures, and can be the basis for the application of artificial neural networks (ANN) to design the composition of concrete.

2. METHODOLOGY

2.1 Materials

The local materials used from Northern Poland and portland ordinary CEM I 42.5R type Portland cement were used. The physical properties of cement are presented in Tab.1.

Table 1: Physical properties of cement

Cement Type	Setting Start Time [min]	Setting End Time [min]	Compressive Strength [MPa]		Blaine Fineness [cm^2/g]	Loss of Ignition [%]	Water Demand [%]
			After 2 [days]	After 28 [days]			
CEM I 42.5R	155	195	30.2	57.3	3504	3.4	27.5

The natural rounded, washed aggregate was used in the research Fig.1. The graining of the aggregates is shown in Fig. 2. Clean water was used without impurities. Admixtures and additives in this research were not used.

a) sand 0-2mm b) gravel 2-8mm c) gravel 8-16mm

Fig.1: The aggregate using in research.

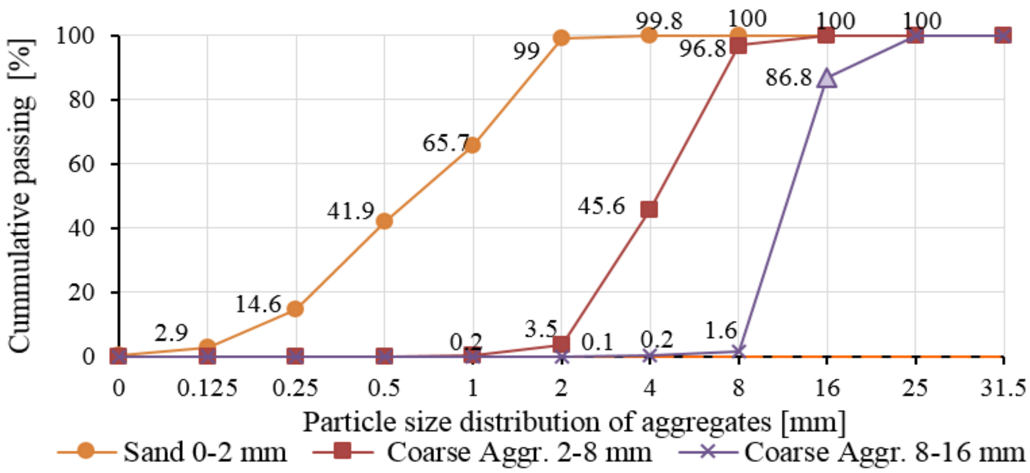

Fig.2: Granular gradient curve for mix aggregates.

2.2 Methods

2.2.1 Design of concrete composition according to Abrams's Law and the modified Bolomey method (Three Equations).

The design steps of the composition of the concrete mix according to the Abrams law were as follows: 1/ definition of compressive strength f'_C; 2/ definition of the required workability (medium and very high); 3/ the Abrams equation used to design the compressive strength of concrete, through cement/water ratio $(\frac{W}{C})$, according to the Eq. (1).

$$f'_C = \frac{A}{B^{(\frac{W}{C})}} \qquad (1)$$

where *A*, and *B* are empirical constants, *W* – water, *C*- cement.

These formulae used with appropriate calibration of constants *A* and *B*, allowing for local conditions, specified properties of components (aggregate), quality of curing, etc. Based on 28 days of compressive strength, other mechanical parameters like splitting strength be calculated from standardized formulae. All calculations of the results was presented in Tab. 4.

The design steps of the composition of the concrete mix according to the Bolomey method the steps were as follows: 1/ definition of compressive strength f'_C'; 2/ definition of the required workability (medium and very high); 3/ the Bolomey method as Three Equation used to design the compressive strength of concrete, through cement/water ratio (*W*/*C*), according to Eq. (2) and (3).

The modified Bolomey method by Brandt 2009, is based on the solution of three linear equations, which expressed strength, materials density, and water requirements of particular fractions of aggregate. The compressive strength was calculated after the so-called Bolomey formula from Eq. (2-5) as follows:

$$f'_C = A_1 \cdot \left(\frac{1}{W/C} - 0.5\right) \qquad \text{for } w/c > 0.4 \qquad (2)$$

$$f'_C = A_2 \cdot \left(\frac{1}{W/C} + 0.5\right) \qquad \text{for } w/c \le 0.4 \qquad (3)$$

where: f'_C – characteristic compressive strength, *C*- cement, *W*-water and both constants A_1 and A_2 considered after the quality of cement and aggregate.

The value of the coefficients A1 and A2 depend on the cement's compressive strength and aggregate shape. It is done by defining them from Tab. 2, where the coarse aggregate used in the concrete mixtures was rounded shape and the compressive strength of the cement type is CEM I 42.5R. The value of each of the coefficients was: A_1 = 20 MPa and the coefficient A_2 =13 MPa.

Table 2: Coefficient of A_1 and A_2 values.

Aggregate shape	Variable (A)	Compressive strength of cement (MPa)		
		32.5	42.5	52.5
Rounded	A_1	18.0	20.0	21.0
	A_2	12.0	13.0	14.5
Angular	A_1	24.0	22.0	20.0
	A_2	16.0	14.5	13.5

By means of the second equation Eq.(4), it is possible to calculate the amount of water required to obtain the required consistency of the concrete mix. In our case, medium and very high consistency were adopted.

$$W = C \cdot w_C + A \cdot w_A \qquad (4)$$

where: *W*- water, *A* – aggregate, *C* – cement, w_c i w_A - index by Stern, for cement and water respectively. Index by Stern is the water needed to moisten 1 kg of the specified aggregate fraction to obtain the required consistency and workability.

Table 3: Water index by Stern for aggregate (w_A) and cement (w_c)

Sieve size (mm)	Workability	
	Medium	Very High
16 – 31.5	0.016	0.022
8 – 16	0.020	0.027
4 – 8	0.026	0.034
2 – 4	0.032	0.044
1 – 2	0.043	0.058
0.5 – 1	0.058	0.077
0.25 – 0.5	0.084	0.112
0.125 – 0.25	0.122	0.151
0 - 0.125	0.239	0.296
cement w_c	0.275	0.310

In this Bolomey method, the unknown values were *W/C*, *C*-cement and *A*-aggregate. As in other methods minimum amount of cement and aggregate grading were imposed by standard regulations.

The third equation takes into account the sum of the volumes of all components which should be 1 m^3. The formula is as follows Eq.(5):

$$\frac{C}{\rho_C} + \frac{A}{\rho_A} + w = 1.0 \ \ [\mathrm{m}^3] \qquad (5)$$

Where: *C*-cement and *A*-aggregate and ρ_C and ρ_A are specific densities of cement and aggregate, respectively.

The results of the calculation are presented in Table 5

2.2.2 Experimental Tests

In this study, designs of concrete mixes with assumed strengths of 25, 30, 35, 40 and 45 MPa were made. Moreover, calculations of the concrete composition were made taking into account two cases of concrete mix liquidity. It was assumed that the mixes will have medium and very high workability. Two methods of concrete design were used: the modified Bolomey method (Three Equation), therefore the composition of the mixtures is significantly different in both cases. The compositions of individual concretes are presented in Tab. 4 and Tab. 5. In total, 20 mixes were designed. From each mixture, 6 cubic samples about dimensions 150 mm x 150 mm x150 mm were made for the compressive strength test within 28 days and 3 cylindrical ϕ150mm x h300 mm samples for the splitting strength test using the Brazilian method.

Concrete components were mixed in a mechanical mixer. The consistency was measured by the slump test (Fig.3). Then the mix was placed in PVC molds and compacted on a vibrating table for 2 min, according to EN 12390-1. Samples were stored until testing in a special room with a humidity of 90±5% (Fig.4). Test specimens were stored for 24 h in molds at the temperature of 20 ± 2 °C, followed until testing time by subsequent storage in a special room with a humidity of 95–100% and a temperature of 20 ± 2 °C. One hour before the test, the specimens were taken out from the chamber and left to dry in the air at a temperature of 20±2°C, according to EN 12390-2:2019. The compressive strength of each concrete was tested on cubic samples according to EN 12390-3 by means of an Advantest 9 Controls machine (Advantest 9, Controls, San Maurizio Canavese, Italy) with a maximum pressure force of 3000 kN according to EN 12390-4, Fig.5. Compressive strength was tested according to EN 12390-3:2019 and was determined as an arithmetic mean of six measurements, along with the calculation of standard deviation of each batch. The tensile strength of concrete with the Brazilian method was made according to EN 12390-6, Fig.6.

Fig.3: The slump test.

Fig.4: Curing the concrete samples.

Fig.5: The compressive strength test.

Fig.6: The splitting test.

3. RESULTS

Table 4 presents the results of calculations by the Abrams law for the composition of concrete classes 25, 30, 35, 40 and 45 MPa, as well as the results of compressive and splitting strength tests. Mainly the content of cement in the composition of concrete as the main component generating CO_2 emissions was analyzed. As for the correlation between the cement content and the compressive strength, it can be seen that in the case of concrete of the 25MPa class, the obtained strength was 8% lower than that designed for the medium workability and 21.6% lower in the case of workability very high. The W/C ratio = 0.78, while the cement content for the assumed workability was 180 kg/m^3 and 225 kg/m^3, respectively. On the basis of the obtained test results, it can be concluded that the W/C ratio calculated according to the formula Eq. (1) is too high, therefore the concrete strength was lower than required. In the case of the designed concrete strength class of 30, 35, 40 and 45 MPa, higher results, even up to 17%, were obtained. The smallest difference between the design strength and the actual strength tested on the samples concerned the strength of 30 and 35 MPa and ranged from 0% to 12%. So it can be said that in the range of 30-35 MPa, the Abrams law turned out to be the best for design. The tests of concrete splitting strength showed that the test results for individual classes ranged from 1.7 MPa to 3.5 MPa and differed, depending on the workability, from average and very high, from 3% to 15%, respectively.

Table 4: Calculation results and compressive and splitting strength tests according to Abram's method.

Type of workability	Design compressive strength (MPa)	Water to Cement (W/C)	Cement content (kg/m^3)	Aver. compressive strength after 28 days (MPa)	Aver. splitting strength after 28 days (MPa)
Medium	25	0.78	180	23.0	2.0
Very high	25	0.78	225	19.6	1.7
Medium	30	0.68	219	29.8	2.2
Very high	30	0.68	271	31.6	2.5
Medium	35	0.60	264	39.3	3.0
Very high	35	0.60	325	37.8	2.9
Medium	40	0.53	323	47.0	3.3
Very high	40	0.53	393	43.3	3.2
Medium	45	0.46	414	49.6	3.4
Very high	45	0.46	497	52.0	3.5

Table 5 shows the results of calculations and laboratory tests according to the Bolomey method. It can be noticed that in the case of calculations made with this method, the W/C ratio for the design strength is much lower than that calculated according to the Abrams method and amounts to W/C = 0.57. As you might expect, the compressive strength was much higher than the designed one, because by as much as 45%. Consumption of cement for class 25 and medium and very high workability was 286 kg/m^3 and 351 kg/m^3, respectively. For the designed concrete strengths of 30, 35, 40 and 45 MPa, the W/C index decreased from 0.5 to 0.33, and along with that, the cement content increased from 356 kg/m^3 to 982 kg/m^3. The strength was higher from 37% to 57%. The splitting strength ranged from 2.5 to 4.4 MPa. It can be clearly stated that the calculation according to the Bolomey method (Three Equations) generates a very high consumption of cement, and does not cause growth significantly increase the strength of the concrete.

Table 5: Calculation results and compressive and splitting strength tests according to Bolomey method.

Type of workability	Design compressive strength (MPa)	Water to Cement (W/C)	Cement content ($kg/$m^3)	Aver. compressive strength after 28 days (MPa)	Aver. splitting strength after 28 days (MPa)
Medium	25	0.57	286	36.1	2.5
Very high	25	0.57	351	36.4	3.1
Medium	30	0.50	356	41.1	3.1
Very high	30	0.50	432	44.7	2.6
Medium	35	0.44	451	49.7	3.0
Very high	35	0.44	538	52.9	2.9
Medium	40	0.39	579	55.7	4.1
Very high	40	0.39	678	52.7	3.7
Medium	45	0.33	879	58.4	4.3
Very high	45	0.33	983	62.3	4.4

Figure 7 shows the change in compressive and splitting strength depending on the change in the *W/C* ratio.

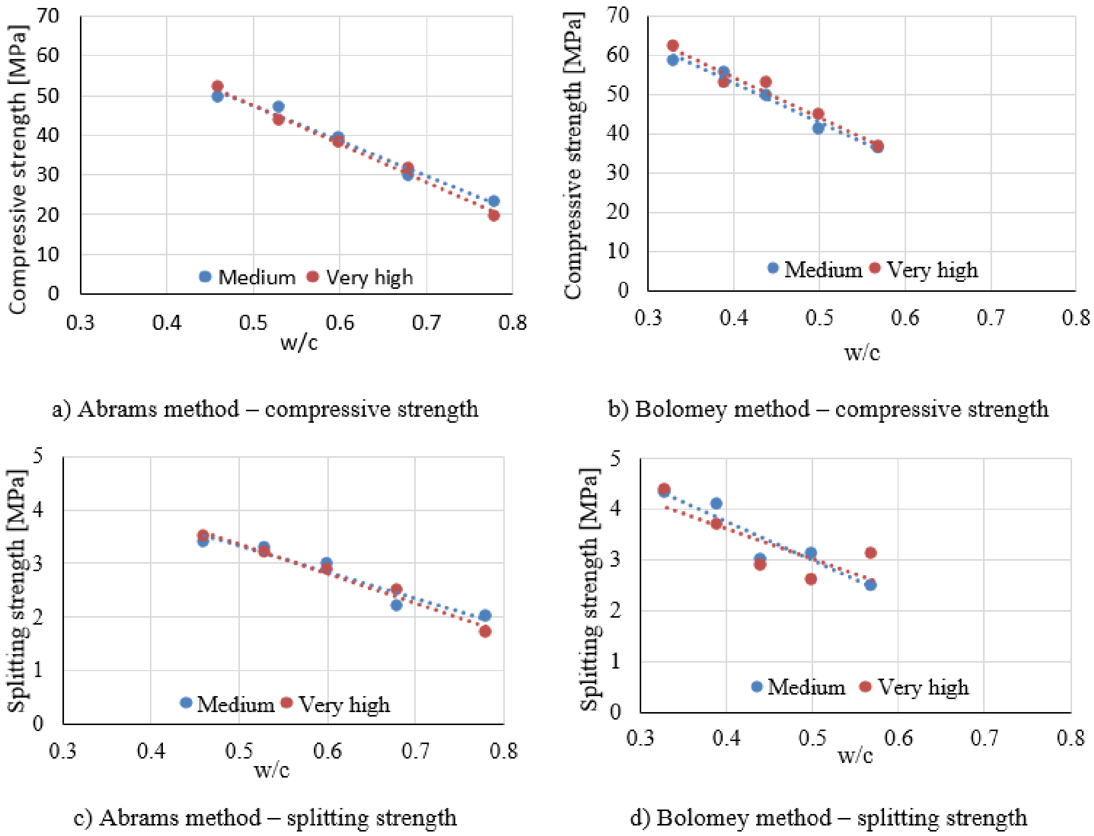

Fig.7: Relationship between the compressive and splitting strength and *W/C* ratio for medium and very high workability according to Bolomey method's and Abrams law.

Figure 8 shows the relationship of compressive strength with the W/C ratio for medium and very high workability, determined according to Bolomey method and Abrams's law. The figure shows the compressive strength vs. cement consumption. From the results obtained, it can be seen that the Abrams law is characterized by a better optimal consumption of cement vs. compressive strength, especially above a compressive strength of 25 MPa.

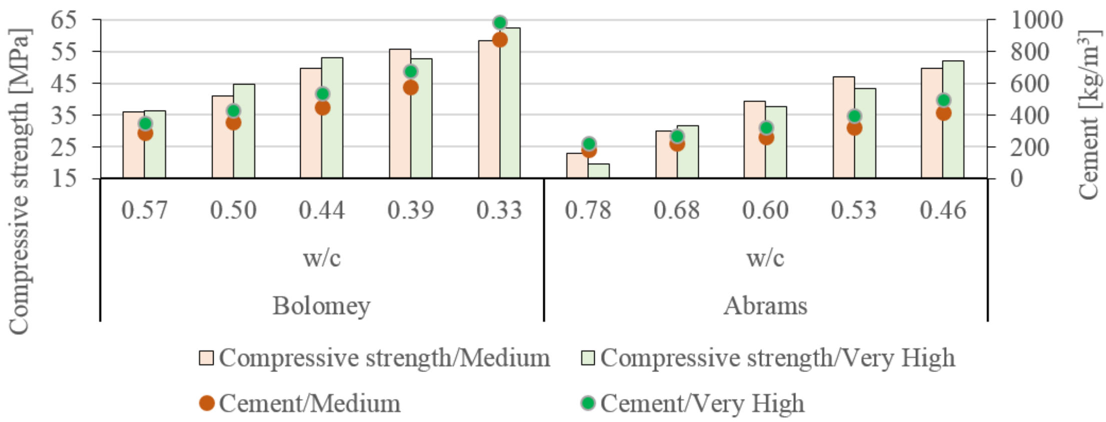

Fig.8: Relationship of compressive strength vs. cement consumption with the *W/C* ratio.

4. CONCLUSIONS

Based on the obtained test results concretes with specific compressive strength: 25, 30, 35, 40 and 45 MPa and the assumed medium and very high workability, it can be concluded that there are significant differences depending on the design method used. Basic differences characterizing Abrams's law and Bolomey methods can be formulated.

1- Both methods are easy to apply and are therefore widely used mainly in Europe.

2- The analysis of the cement content in the composition of 1m^3 of the mixture showed very large differences depending on the calculation method used. The cement content calculated according to the Abrams method ranged from 180 kg/m^3 (25MPa) to 497 kg/m^3 (45MPa) depending on the class and determined according to the Bolomey method from 286 kg/m^3 (25MPa) to 983 kg/m^3 (45MPa).

3- By analyzing the results of the compressive strength tests, it was confirmed that the compressive strength depends on the water/cement ratio. In the case of applying the Abrams law, the W/C ratio was from 0.78 and decreased to 0.46, while the compressive strength was from 19.6 MPa to 52.0 MPa, respectively. The W/C ratio for concretes designed according to the Bolomey method was lower varied from 0.57 to 0.33, while the compressive strength was from 36.1 MPa to 62.3 MPa.

4- In designing concrete, the selection of the design method is important due to the possibility of calculation of the concrete mix composition and obtaining the precisely and compliant with the requirements strength. The calculation method should allow the most precise prediction of concrete strength. Based on the research, it was noticed that the standard deviation of the results did not exceed 2% in any case (for 6 samples tested for each class and for each assumed workability). In the case of the designed concrete strength class of 30, 35, 40 and 45 MPa, higher results, even up to 17%, were obtained. The smallest difference between the design strength and the actual strength tested on the samples concerned the strength of 30 and 35 MPa and ranged from 0% to 12%. According to Bolomey method the strength was higher from 37% to 57% when analyzing research for all concrete classes. So the endurance was significantly overstated.

5- Compressive strength vs. cement consumption showed that the Abrams law is characterized by optimal cement consumption, especially when determining the composition of concretes with compressive strength above 25 MPa. It can be said that in the range of 30-35 MPa, the Abrams law turned out to be the best for design.

6- The tests of concrete splitting strength calculated by Abrams law ranged from 1.7 MPa to 3.5 MPa and differed, depending on the workability from 3% to 15%, respectively, while according to the Bolomey method the splitting strength ranged from 2.5 to 4.4 MPa and results differed to 15%.

7- A cement content of more than 450 kg/m^3 is not desirable, primarily from an environmental and economic point of view.

8- It can be clearly stated that the calculation according to the modified Bolomey method (Three Equations) generates a very high consumption of cement, and does not cause growth significantly increase the strength of the concrete.

An example is the designed concrete class of 45 MPa. In this case, the amount of cement according to the calculations was 983 kg/m^3 and the compressive strength in this case was 62.3 MPa.

9- Probably the use of chemical admixtures along with the correction of the water content would increase the strength concrete calculated according to both methods. However, attention should be paid to the fact that concrete admixtures are selected depending on the type and amount of cement. Therefore the cement content in 1m^3 mix concrete is also important for economic reasons, because the higher the cement content, the greater the admixture consumption.

10- Summarizing the above, bearing in mind the protection of the environment, it is necessary to select the appropriate methods of concrete design, taking into account cement admixtures and substitutes.

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- EN 12390-3 Concrete tests -Compressive strength of the samples
- EN 12390-4 Concrete tests-Compressive strength. Universal testing machines specification

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- EN 12390-3 Testing Hardened Concrete-Part 3: Compressive Strength of Test Specimens.
- EN 12390-6 Testing hardened concrete-Part 6: Tensile splitting strength of test specimens.