

UNIVERSITATEA TEHNICĂ DE CONSTRUCȚII BUCUREȘTI
ȘCOALA DOCTORALĂ

**RESEARCH REPORT – LABORATORY STUDY ON THE
INFLUENCE OF STANDARD SAND ADDED TO TO WATER-
CEMENT-BENTONITE MIXTURE**

PhD Supervisor ,

Prof. Dr. Eng. Anton CHIRICĂ

PhD Candidate,

Eng. Cristian-Ștefan BARBU

October 2022

TABLE OF CONTENTS

Table of figures	3
1 Introduction.....	4
1.1 Studii anterioare	4
1.2 Objectives.....	7
2 Mixtures obtaining procedure.....	8
2.1 Materials.....	8
2.1.1 Standard sand.....	8
2.1.2 Cement and bentonite	9
2.1.3 Mix design	10
3 Testing methods.....	13
3.1 Viscosity testing.....	13
3.2 Permeability coefficient	14
3.3 Compressive strength testing	15
4 Laboratory testing results.....	18
5 Conclusions.....	25
6 Bibliography	27

TABLE OF FIGURES

Fig. 1.1: Possible mixtures presented on the surface of the ternary diagram	4
Fig. 1.2: Restriction of the study domain	5
Fig. 1.3: Boundaries of recommended water-bentonite-cement mixtures based on the test results	7
Fig. 1.4: Representation on the ternary diagram of the mixtures used in Research report no. 3	8
Fig. 2.1: Grain size distribution of standard sand	9
Fig. 2.2: Mixing methods for obtaining plastic concrete [1]	10
Fig. 2.3: The aspect of a group of samples with the same water-cement-bentonite ratio after removing the cast	11
Fig. 2.4: The aspect of a group of samples with the same water-cement-bentonite ratio after removing the cast	12
Fig. 2.5: Samples affected by cracking	12
Fig. 3.1: Viscosity testing of the material in fresh state	13
Fig. 3.2: Sample before and after testing	14
Fig. 3.3: Group of samples after testing	16
Fig. 3.4: Group of samples after testing	17
Fig. 3.5: Samples containing larger quantities of concrete after testing	17
Fig. 4.1: Variation of permeability coefficient on the study domain considering different sand to solids ratios	18
Fig. 4.2: Variation of compressive strength on the study domain considering different sand to solids ratios	19
Fig. 4.3: Variation of viscosity on the study domain considering different sand to solids ratios	21
Fig. 4.4: The variation coefficient for compressive strength	22
Fig. 4.5: The variation coefficient for permeability coefficient	23

1 INTRODUCTION

Most of the information presented within this research report was published at the conference „22nd International Scientific Multidisciplinary Conference on Earth and Planetary Sciences SGEM 2022”. The article is entitled „Water/Cement/Bentonite Mixtures Property Testing in the Presence of Standard Sand”

1.1 Studii anterioare

In the previous research report – “Laboratory study on the ratio between the plastic concrete components” there was conducted a testing program of water-cement-bentonite mixtures which was purposed to analyse the relation between water-cement-bentonite and to establish optimal mixtures from the mass percentages point of view and also, from the material performance standpoint. Also, during previous studies it was proposed a different approach regarding the representation of the obtained results (compressive strength, permeability coefficient and viscosity), these being presented on the surface of a ternary diagram on which the components of the mixtures are expressed as mass percentages.

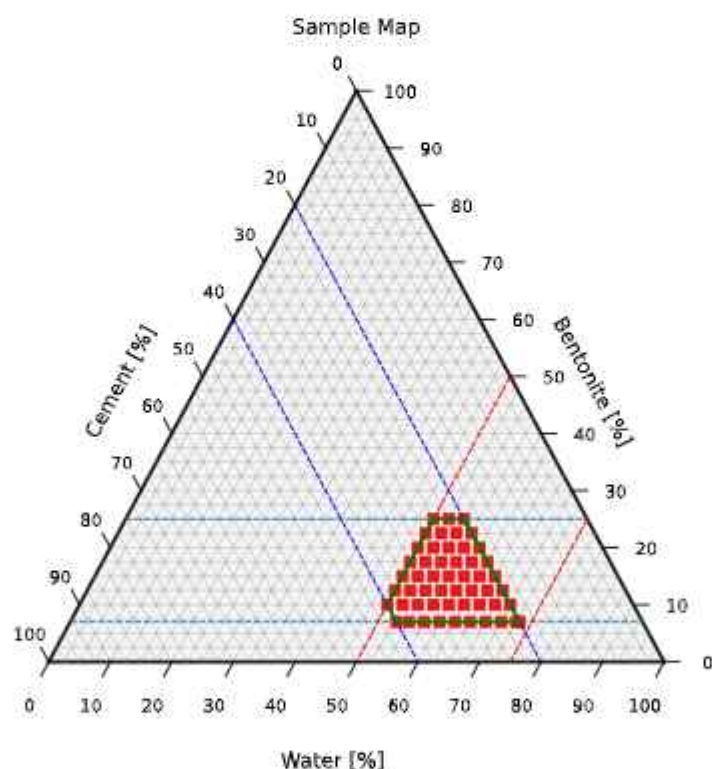


Fig. 1.1: Possible mixtures presented on the surface of the ternary diagram

Starting from the study of the speciality literature, in order to analyse the relation between water, cement and bentonite, there were manufactured 52 mixtures which were designed to cover as vast as possible the entire surface of the ternary diagram. The values of the mass ratios from previous papers which were documented for this paper are presented in Tab. 1.

In the early stages of the laboratory study, it was observed that, after removing the cast, because of the lack of aggregate, the samples developed cracks. For this reason, for the manufacturing of the samples it was used standard sand, according to EN 196-1 – Methods of testing cement. Part 1: Determination of strength. The ratio used was 1:1 with respect to the solid mass of the mixture (mass of cement and bentonite).

Tab. 1: Ratio between components extracted from previous contributions

Paper reference	Water-cement ratio	Water-bentonite ratio	Bentonite-cement ratio
Research report no. 2	1.25÷3.65	2.00÷10.40	0.175÷1.25
Shepherd et al, 2020 [1]	3.30÷10.00	-	0.10÷0.24
Fadaie et al, 2019 [2]	1.60÷2.00	8.00÷20.00	0÷0.40
Pisheh et al, 2018 [3]	1.80	6.30÷10.20	0.14÷0.29
US Dept. of Interior, 2014 [4]	1.00÷2.78	6.67÷13.90	0.10÷0.22
Hinchberger et al, 2010 [5]	1.70÷2.35	12.50÷18.20	0.20÷0.30
Bagheri et al, 2008 [12]	1.80÷2.60	13.00	0.14÷0.23

Considering that an excessive quantity of one of the components has a negative influence on the obtained material, the mass percentages were limited in the case of each component such that feasible mixtures could be obtained. In this way, it was established a subdomain of the ternary diagram on which the parameters determined during the laboratory testing could be represented (Fig. 1.2).

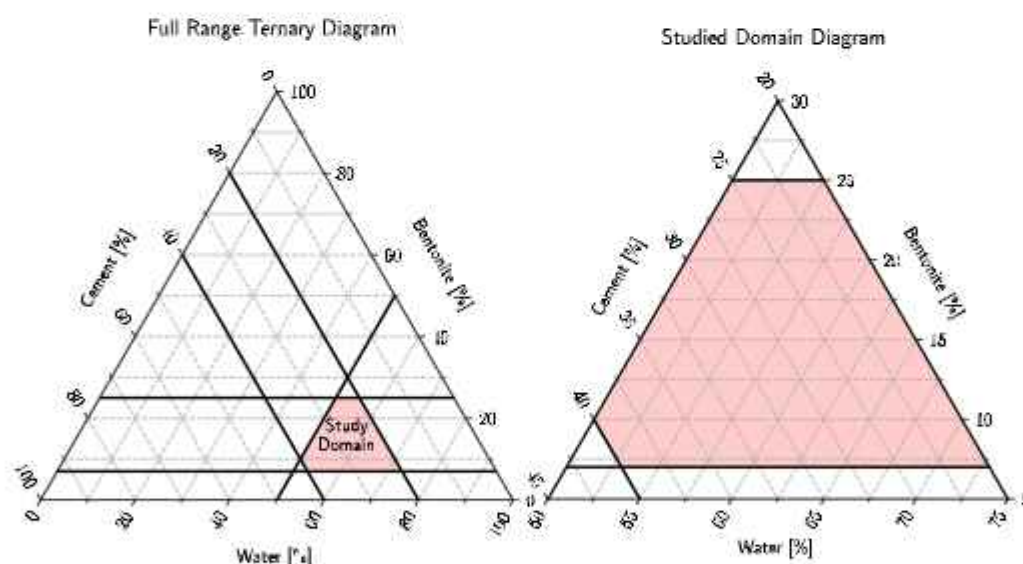


Fig. 1.2: Restriction of the study domain

The proposed testing program was composed of laboratory tests for the determination of the following parameters:

- viscosity;
- permeability coefficient;
- compressive strength.

The sample manufacturing process was done in laboratory conditions and implied the realization of a dry mixture (cement, bentonite and sand), adding the necessary water quantity and then, the mixture of all components until a homogeneous paste was obtained, without local accumulation of material.

For the obtained samples it was necessary a 28-day period in order to assure the fact that the material reached its strength and the hydration and cementation bonds were established. After this period the testing began.

The conclusions of the study were influenced by factors such as: the large spread of the domain study (52 mixtures), the tests being done on one sample and also the time span necessary for testing. Despite these factors, it could be concluded that:

1. There is the possibility to define an area of optimal mixtures on the proposed ternary diagram, considering also the fact that the mixtures were done with materials already studied and tested;
2. The excessive use of one of the components leads to unwanted phenomena such as cracking or segregation. Also, it was demonstrated that the predominant use of one component is visible for sensitive percentage variations. A good example is the use of bentonite which, after a certain threshold, does not contribute to the water retention capacity, but has a negative influence on permeability and on compressive strength;
3. It is necessary the extension of the study. In order to have a sufficient reliability degree on the testing program results, it is necessary to manufacture at least 3-5 samples of each mixture;
4. It is necessary to establish a sufficient quantity of standard sand which should prevent cracking and, also, to not influence the water-retaining and strength capacity of the mixtures.

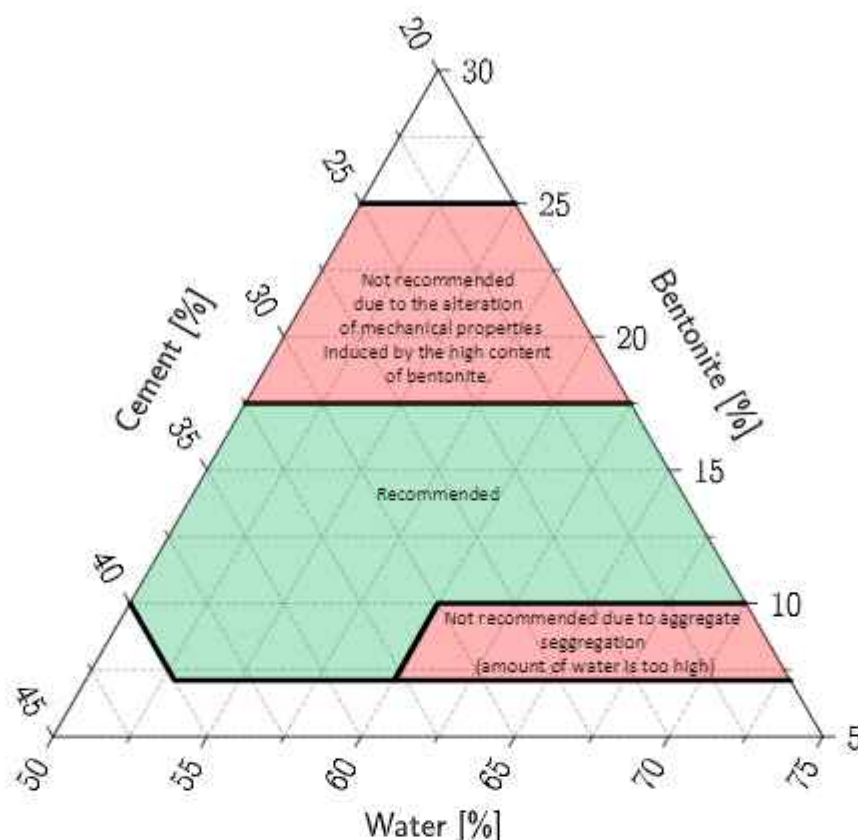


Fig. 1.3: Boundaries of recommended water-bentonite-cement mixtures based on the test results

1.2 Objectives

Starting from the information gathered during the previous laboratory studies conducted for this research, it was determined a surface on the ternary diagram on which there are represented the mixtures with a satisfactory mechanical and hydraulical behaviour. In the first part of the study, the research based on a ratio between the standard sand and solid (mass of bentonite and sand) part of 1:1.

In the third research report, the proposed objective is to determine the sufficient quantity of standard sand to be used in mixtures which prevents the consequences of contraction and hydration of the binder and also, it is sufficient to not intervene on the mechanical and hydraulical properties of the obtained material. In order to determine the influence of the standard sand, during this stage of the research were used 4 ratios of standard sand to solids, starting from 0.5:1 to 4:1.

By using the ratio of 0.5:1, the sand quantity used in the first part of the study was halved, in this way covering the inferior limit of sand quantity that could be used for mixture preparation. Considering that in the precedent study the ratio used was of 1:1 and that on the surface of some samples some cracking was noticed, it was supposed from the beginning that this ratio will not be sufficient for reaching the proposed goals. On the other side, the ratio of 4:1 involves a large quantity of standard sand which will have a considerable impact on the physical parameters of the material.

Therefore, on the optimal surface of the ternary diagram there were selected eleven water-cement-bentonite mixtures. For the chosen mixtures there were prepared 4 samples, the latter being differentiated by the ratio of standard sand to solids ratio: 0.5:1, 2:1, 3:1 și 4:1 (Fig. 1.4). Așadar, pe suprafața optimă a diagramei ternare au fost alese unsprezece amestecuri apă-ciment-bentonită realizate și în prima parte a studiului. Pentru amestecurile alese au fost confecționate 4 probe, acestea fiind diferite prin raportul nisip standardizat-parte solidă utilizat: 0.5:1, 2:1, 3:1 și 4:1 (Fig. 1.4).

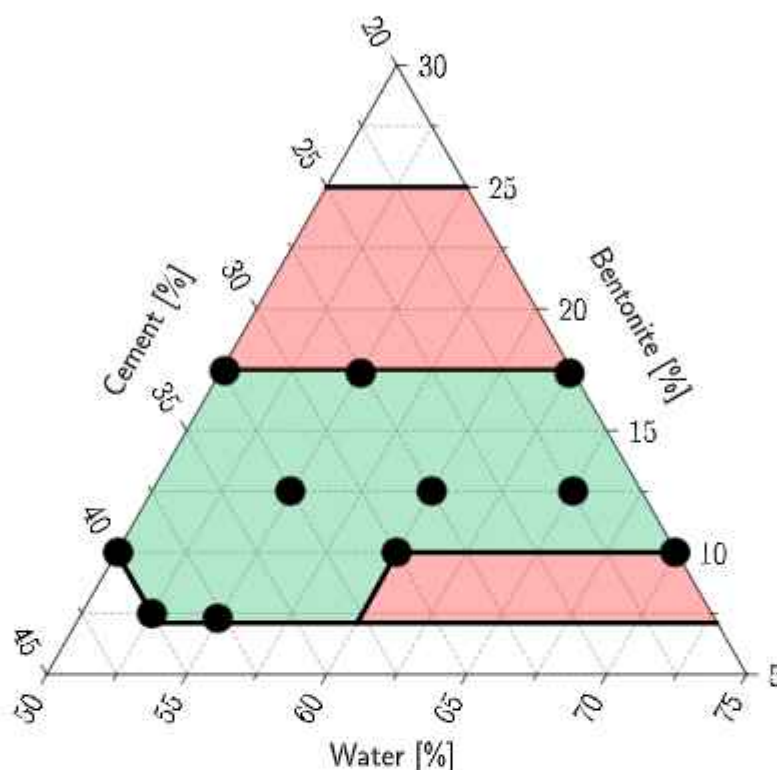


Fig. 1.4: Representation on the ternary diagram of the mixtures used in Research report no. 3

2 MIXTURES OBTAINING PROCEDURE

2.1 Materials

2.1.1 Standard sand

For sample preparation there was used standard sand as it is defined in EN 196-1 – Methods of testing cement. This material is a natural, silicious sand made of round particles, having a minimum 98% silicium content. The grain size distribution of this material is presented in Tab. 2.

Pentru confecționarea probelor a fost utilizat nisip standardizat așa cum este definit de standardul EN 196-1 – Metode de încercări ale cimenturilor. Determinarea rezistențelor mecanice. Acest material este un nisip natural, silicios, alcătuit din particule rotunde, cu un conținut de siliciu de minim 98%. Distribuția granulometrică a acestui material este prezentată în Tab. 2.

Tab. 2: Grain size distribution of standard sand [7]

Square mesh size (mm)	2.00	1.60	1.00	0.50	0.16	0.08
Cummulative sieve residue (%)	0	7±5	33±5	67±5	87±5	99±1

According to the standard, the sand used in the mixture was dried at $105\pm 110^{\circ}\text{C}$, maintaining a moisture content of maximum 0.2%.

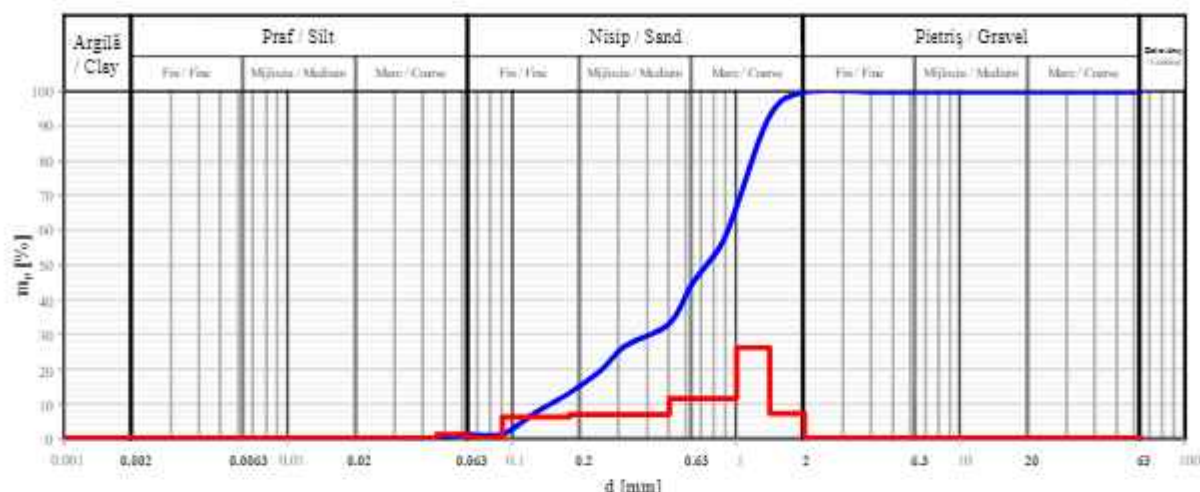


Fig. 2.1: Grain size distribution of standard sand

If in the first part of the study a ratio between the standard sand and solids of 1:1 was employed, in order to reach the proposed goals for this testing stage there were proposed four other values for the ratio: 0.5:1, 2:1, 3:1, 4:1. By using these sand quantities, it was studied the mixtures behaviour under different aggregate masses and the evolution of the physical and mechanical parameters.

By using standard sand, it was proposed the determination of its influence on the strength and permeability of the sample, even though it does not intervene on the internal hydration mechanisms, having a negligible activity in relation to water and to the other elements.

2.1.2 Cement and bentonite

The hydraulic binder used for manufacturing the samples is Portland cement with high initial strength (20MPa), and with ultimate compressive strength of 42.5MPa (CEM IIA 42.5R).

The use of sodium bentonite was employed, which regularly is used for preparing the drilling fluids. The calcium bentonite has the capacity to improve the viscosity of the drilling fluid and has hydro insulating properties. According to the technical sheet offered by the manufacturer, its characteristics are presented in Tab. 3.

Tab. 3: Characteristics of the bentonite used for sample manufacturing [8]

Characteristics	Admissibility conditions
Color	White-gray
Maximum grain size	sieve Ø0.16mm – max. 15% sieve Ø0.063mm – max. 25%
Performance	min. 8mc/to
Moisture content	max. 10%
Free sand	max. 10%
ph	9-10

The use of common, studied materials was employed for the laboratory testing stage of the study such that results could be significant, with the possibility of applying them in current execution situations.

2.1.3 Mix design

In the reference papers there were stated three methods of mix design for water-cement-bentonite mixtures, presented in Fig. 2.2.

Method A involves preparing the bentonite slurry 24 hours before in order to allow the hydration of the material, later introducing the cement and the aggregates [1] [5] [6] [9]. Method C treats this issue similarly, allowing a pre-hydration stage of maximum 8 hours for the bentonite slurry. These procedures allows working simultaneously for obtaining the dry mixtures made of cement and aggregates, afterwards allowing adding the latter to the hydrated paste.

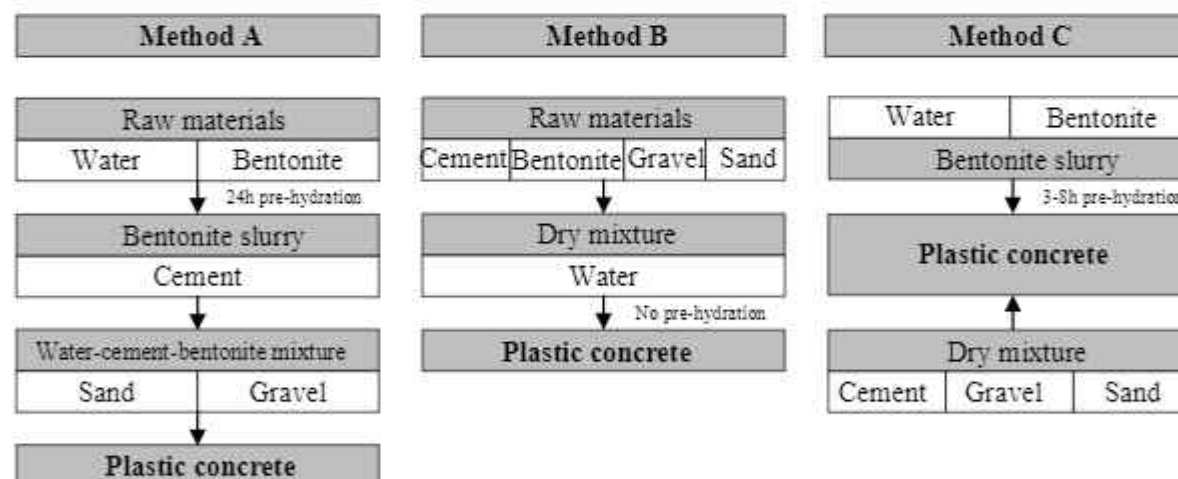


Fig. 2.2: Mixing methods for obtaining plastic concrete [1]

Method B proposes a simplified approach for mix design, involving creating initially the dry mix, then adding the prescribed water quantity. Also, in reference papers it is mentioned that because of different methods and different hydration time, the results could differ function of the mix design solution regarding the mechanical and hydraulical properties of the materials. This fact is attributed to the various hydration methods of the bentonite, which, in its turn influences the hydration of the cement. [1]

Contradictorily, in another study where samples were tested with and without pre-hydration of bentonite, the performances of the plastic concrete are not influenced by the staging of the material obtaining process. Furthermore, it has been observed that after a sufficiently long period, the differences between the properties of samples obtained with or without pre-hydration become insignificant, thus rendering the obtaining procedure of the mixture insignificant. [2]

Considering the applicability in real execution situations, methods A and C presented in Fig. 2.2 pose greater difficulty due to the time required for bentonite hydration as well as due to the impediment represented by the space required to maintain the bentonitic slurry under optimal conditions. Therefore, the decision was made to use method B for preparing the mixture.

In the first phase of sample fabrication, the materials used in the mixture were individually weighed. Subsequently, cement, bentonite, and standardized sand were mixed until uniformity, forming the dry mixture. Water was gradually introduced into the mixture to prevent the formation of local clusters of dry material. Once the entire quantity of water was added, the mixture was kneaded until a homogeneous material was obtained. Proper kneading of the material is crucial for sample fabrication as it prevents the formation of local clusters of unhydrated material, which in turn can lead to segregation or undesired mechanical and hydraulic behaviours.

The material thus obtained was poured into cylindrical plastic moulds with a diameter of 50mm and a height of 100mm, insulated at the bottom to prevent spilling. The shape and dimensions of the moulds were chosen to facilitate testing the material in the triaxial compression apparatus. Before pouring the material into the moulds, a thin film of oil was applied to the inner surface to facilitate removing the cast. (Fig. 2.3 and Fig. 2.4).



Fig. 2.3: The aspect of a group of samples with the same water-cement-bentonite ratio after removing the cast



Fig. 2.4: The aspect of a group of samples with the same water-cement-bentonite ratio after removing the cast

On fresh specimens, immediately after casting, viscosity testing was performed to determine the viscosity, while the tests conducted in the triaxial compression apparatus began at a minimum of 28 days after casting.

According to predictions based on the results of the first laboratory study, on the surface of specimens with a higher water content, combined with a sand-to-solid ratio of 0.5:1, the appearance of shrinkage cracks was observed (Fig. 2.5). Despite the fact that a larger quantity of water ensures better workability of the material, these phenomena affect other properties.



Fig. 2.5: Samples affected by cracking

3 TESTING METHODS

The laboratory program involved testing forty-four samples of water-bentonite-cement mixture, which were subjected to viscosity testing in the fresh state and, after a minimum of 28 days, to compression strength and permeability testing in the triaxial compression apparatus.

Starting from eleven recipes from the optimal mixture zone determined in a previous study, an additional 4 samples were developed for the same recipes. The difference lies in the introduction of a different quantity of standardized sand to meet the condition imposed by the sand-to-solid mass ratio of 0.5:1, 2:1, 3:1, and 4:1.

After removing the cast of the samples, before being introduced into the triaxial compression apparatus, their outer faces were finished. The purpose of finishing is to remove excess material that could cause eccentricities during compression testing.

3.1 Viscosity testing

Immediately after pouring the mixture into the cylindrical moulds, viscosity determination was performed. The equipment used consists of a rotational viscometer, the Haake Viscotester 7 Plus (Fig. 3.1). The apparatus allows for the mounting of various rotational spindles with different geometries, chosen based on the consistency of the tested material. By measuring the resistance on the spindles, the viscosity of the mixture is determined. Considering that the paste is subjected to testing as a quasi-Newtonian fluid, the dynamic viscosity of the material is derived from the slope of τ - $\dot{\gamma}$ curve.



Fig. 3.1: Viscosity testing of the material in fresh state

During the test, several rotational speeds of the viscometer spindle were used, ranging from 0.1 rpm to 100 rpm (Fig. 3.2). The viscosity value was chosen based on the confidence level of the measurement indicated by the apparatus. The use of the lower speed values was preferred due to the susceptibility of some samples to material settling immediately after pouring into the cylindrical moulds



Fig. 3.2: Sample before and after testing

3.2 Permeability coefficient

The permeability coefficient of the samples was determined in the triaxial compression apparatus using the constant head permeameter method. The coefficient of permeability is the ratio between the water velocity v and the hydraulic gradient under which the flow occurs, namely:

$$k = \frac{v}{i}, i = \frac{\Delta h}{l}, k = \frac{Q \times l}{A \times \Delta h} \quad (1)$$

where,

v = water velocity;

i = hydraulic gradient;

Q = water discharge;

A = sample sectional area. [10]

The working procedure for conducting the test consisted of the following operations:

- finishing the top and bottom parts of the sample to obtain a smooth surface without eccentricities;
- weighing the sample and measuring its diameter and height;
- placing porous stones at the ends of the sample and inserting it into the elastic membrane;
- saturation of the water circulation lines in the triaxial compression apparatus;
- installing the specimen on the base of the triaxial compression apparatus;
- isolating the membrane at both ends of the sample using rubber o-rings;
- Installing and securing the cell, filling it with water;

The permeability test using the constant head permeameter method is carried out by applying a water flow through the sample at a constant pressure. In the laboratory study, a constant pressure of 300 kPa was maintained in the cell, while water was introduced through the sample, from bottom to top, at a constant pressure of 280 kPa. The volume of water introduced was continuously measured during the test. The volume of water evacuated was recorded using a digital volume controller.

3.3 Compressive strength testing

The monoaxial compression strength of the tested material was determined in the same apparatus after completing the permeability test. During this test, no additional pressures (e.g., radial pressure) were applied to the sample. The monoaxial compression strength was determined following the guidelines of STAS 8942/6-72: Foundation soil - Uniaxial compression test of soils and EN 17892-7:2018 - Unconfined compression test.

According to STAS 8942/6-76, the uniaxial compression test involves the continuous application of axial loading to the specimen in order to obtain:

- p_c monoaxial compressive strength;
- ϵ , axial strain. [11] [12].

The monoaxial compressive strength can be determined in two ways:

- with constant axial strain rate and measuring the resulting stress;
- with applied stresses and measuring the resulting axial deformations [11] [12].

In the laboratory study, the monoaxial compression test was conducted with a constant axial displacement rate of 1mm/min and the maximum strain was limited to $\epsilon_{max}=20\%$. During testing, the deviator stress acting on the specimen was recorded during the test.

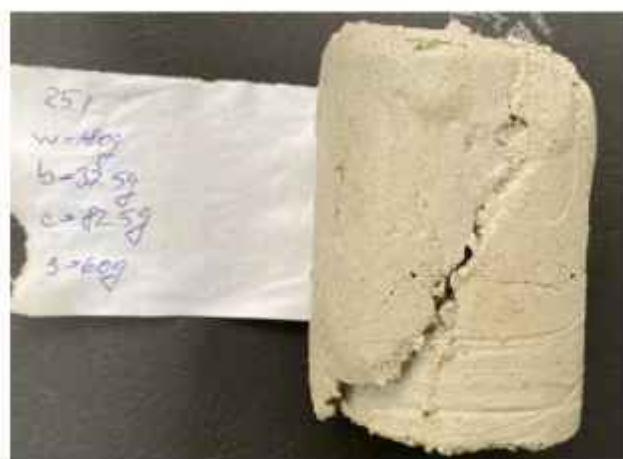
The calculation relation for axial compression strength is established in STAS 8942/6-76:

$$p_c = 2 \times c_u \quad (2)$$

where, c_u – undrained cohesion, measured in N/mm^2 . [11] [12]

After completing the tests, the samples were removed from the elastic membrane and weighed to measure their final mass. Subsequently, they were placed in an oven for 24 hours to determine the dry mass. With this data, the simple indices of the material could be determined.

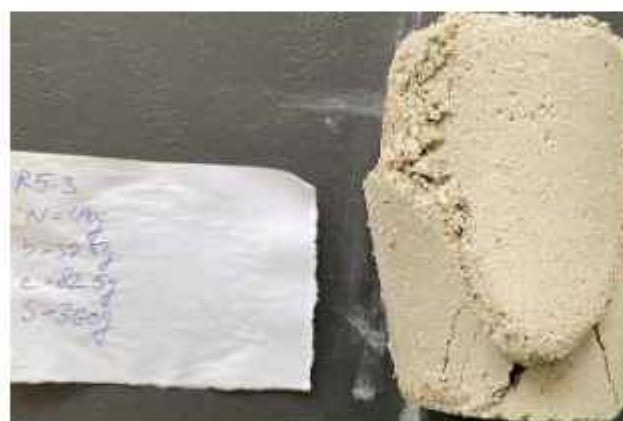
In Fig. 3.3 and Fig. 3.4 samples belonging to the same grouping but with different sand-to-solid ratios are presented. A transition in the yielding mechanism of the material can be observed. In the case of these types of specimens, whose behaviour is not governed by the cement in the mixture, starting from specimens with a sand-to-solid ratio of 0.5:1 up to specimens with a ratio of 3:1, a yielding mechanism similar to that of soils (with a slip plane at 45°) is observed. For the specimen with a ratio of 4:1, yielding by compression, typical of weak concrete, was observed



Ratio 0.5:1



Ratio 2:1



Ratio 3:1



Ratio 4:1

Fig. 3.3: Group of samples after testing

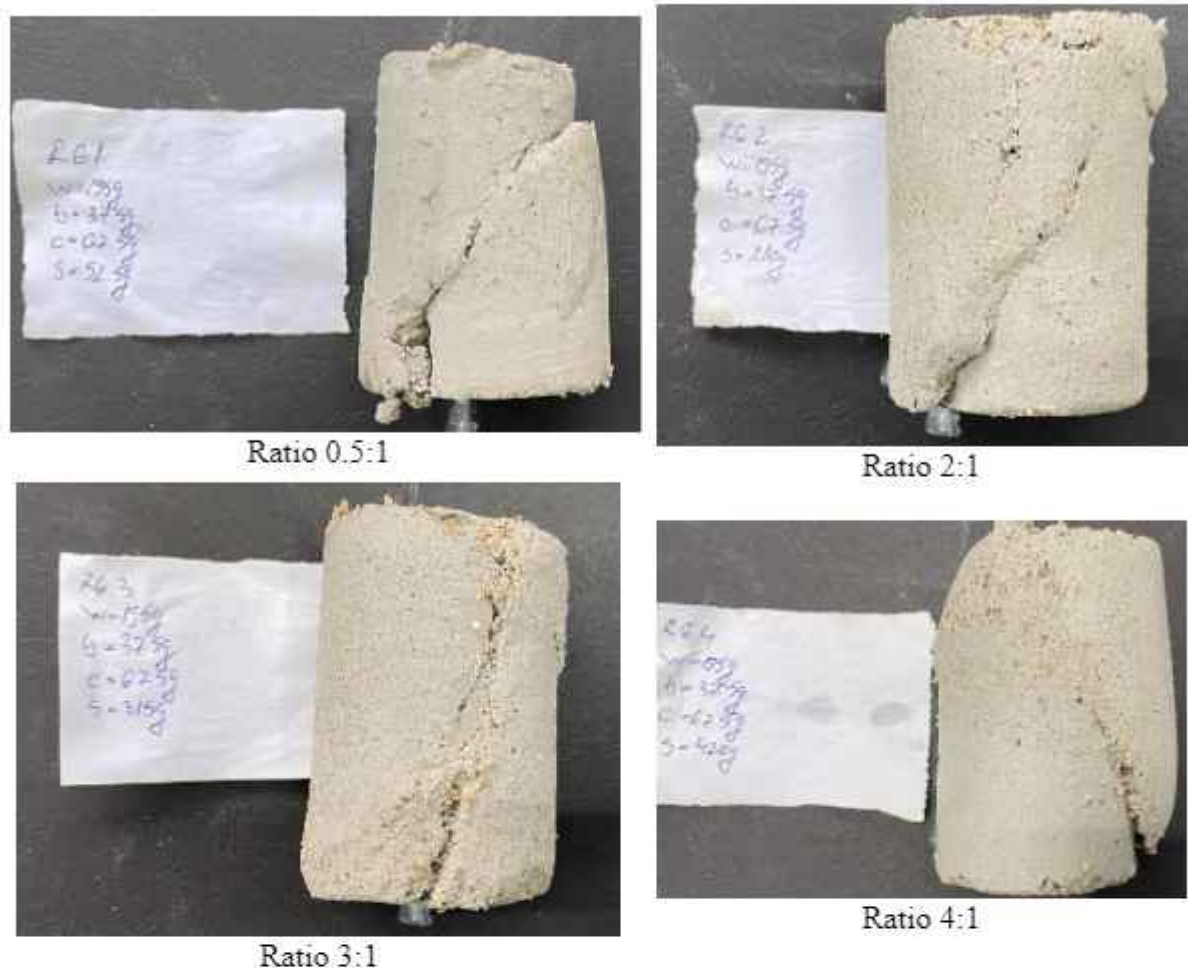


Fig. 3.4: Group of samples after testing

In Fig. 3.5, mixtures with a sand-to-solid ratio of 0.5:1 are presented, governed by the quantity of cement used. For these specimens, it can be observed that even for a reduced amount of aggregate, the yielding mechanism is influenced in this case by the amount of hydraulic binder, with the yielding mechanism being specific to weak concrete, regardless of the amount of sand introduced into the mixture.

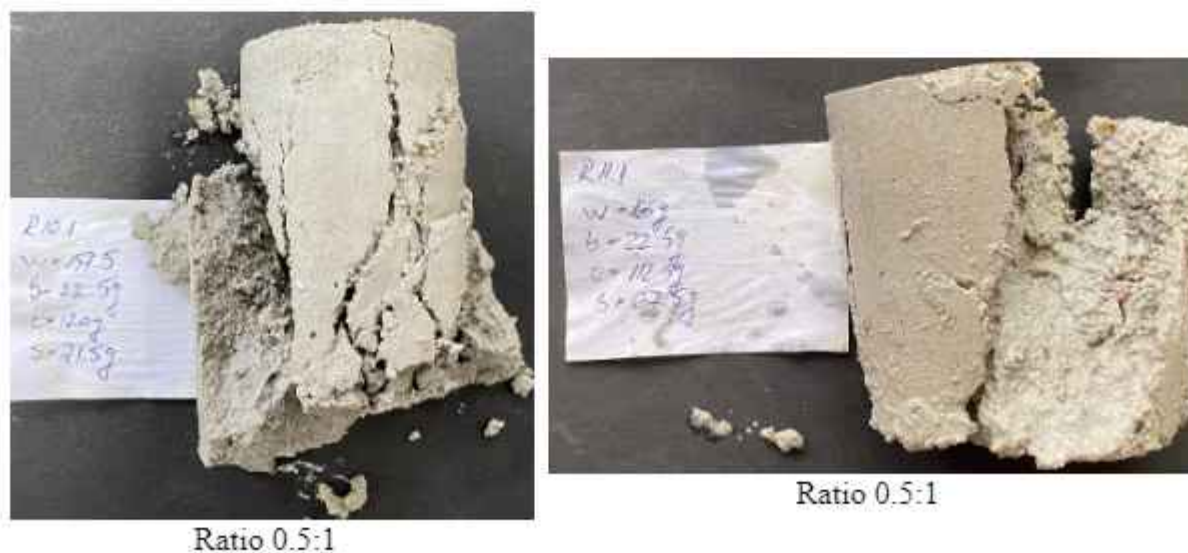


Fig. 3.5: Samples containing larger quantities of concrete after testing

4 LABORATORY TESTING RESULTS

In Fig. 4.1+Fig. 4.3, variations of the parameters determined in the testing program (permeability coefficient, compressive strength, and viscosity) are presented for each sand-to-solid ratio used, namely 0.5:1, 2:1, 3:1, and 4:1. Specifically, in the representations from Fig. 4.1b+Fig. 4.1d, the influence of a larger quantity of bentonite on the mixture is highlighted, showing better hydraulic behaviour of the material regardless of the amount of standardized sand used. Regarding the results obtained for the specimens using a sand-to-solid ratio of 0.5:1 (Fig. 4.1a), they can be considered inconclusive. The small amount of sand used in manufacturing these specimens is the cause of shrinkage phenomena, which in turn have generated cracks in the specimens, thus affecting the results of the laboratory tests. Considering these aspects, it can be concluded that the sand-to-solid ratio of 0.5:1 is insufficient to ensure both the integrity of the mixture and satisfactory hydraulic behaviour. Taking into account the stability provided by the mixture and the fact that a larger quantity of standardized sand does not influence the water retention capacity, it can be affirmed that the sand-to-solid ratio of 2:1 is sufficient to achieve the purpose of fabricating the material.

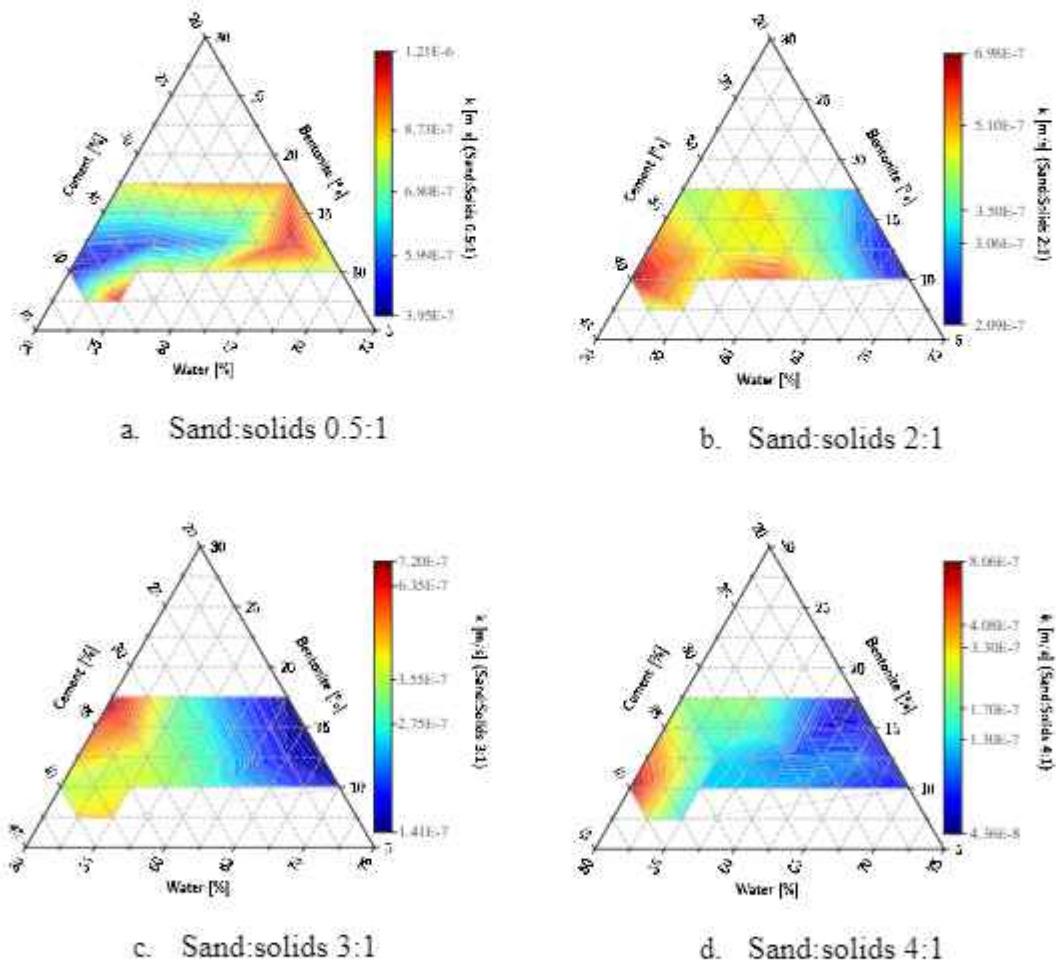


Fig. 4.1: Variation of permeability coefficient on the study domain considering different sand to solids ratios

In Fig. 4.2, the variation of compressive strength across the study domain is presented. As determined in the previous study, compressive strength is a characteristic dominated by the quantity of cement used in the mixture, with samples governed by this factor obtaining the maximum values of the parameter. The use of a larger quantity of cement generates higher compressive strengths.

It is also noteworthy that the sand-to-solid ratio does not interfere with the value or distribution of compressive strength. The similarity of the results is emphasized in the graphs from Fig. 4.2a-Fig. 4.2d. Thus, regarding the influence of the quantity of standardized sand on compressive strength, it can be stated that there is no lower limit for the sand-to-solid ratio. However, in terms of the integrity and stability of the mixture, the ratio of 2:1 between sand and the solid part used in the mixture is considered sufficient.

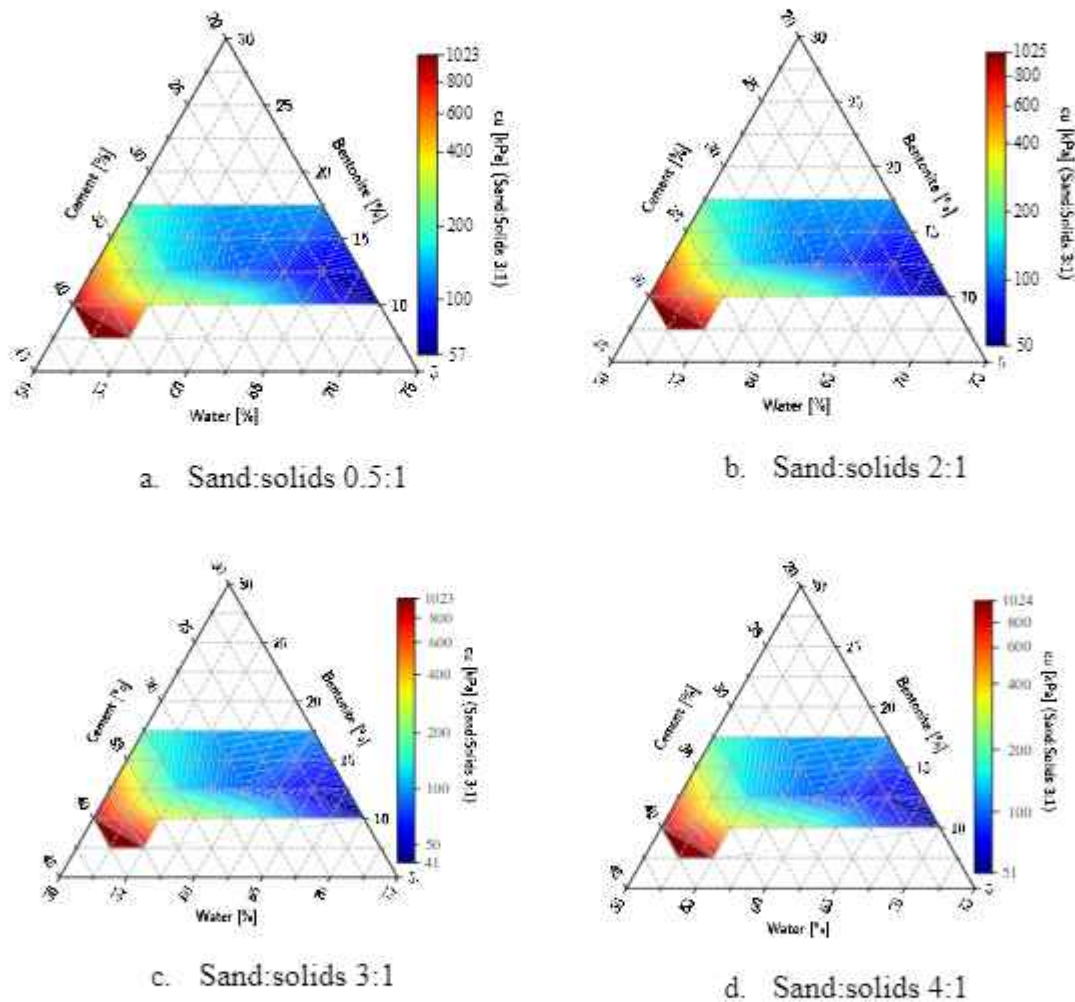


Fig. 4.2: Variation of compressive strength on the study domain considering different sand to solids ratios

The viscosity of the material in its fresh state was measured using a rotational viscometer. From the slope of $\tau-\gamma'$, the dynamic viscosity of the mixture is obtained, under the condition that it is considered quasi-Newtonian. The variation of viscosity is significant, ranging between 0.68 to 401.87 Pa*s. For this reason, in order to achieve a balanced color variation, a normalized logarithmic scale described by equation was used. (3) [13]:

$$\text{norm}(\mu_i) = \frac{\frac{\ln(\eta_i)}{\ln(\prod_{i=1}^n \eta_i)} - \min\left(\frac{\ln(\eta_i)}{\ln(\prod_{i=1}^n \eta_i)}\right)}{\max\left(\frac{\ln(\eta_i)}{\ln(\prod_{i=1}^n \eta_i)}\right) - \min\left(\frac{\ln(\eta_i)}{\ln(\prod_{i=1}^n \eta_i)}\right)} \quad (3)$$

For plotting the graphs, Python 3.9.9 was used along with the libraries: numpy, matplotlib, mpltern, and ternary.

Fig. 4.3 presents the variation of viscosity over the study domain. Viscosity is a characteristic that helps describe the workability of the material in its fresh state. In the first part of the laboratory study, it was demonstrated that this property is controlled by the amount of bentonite and the amount of water introduced into the mixture. However, bentonite has the potential to negatively affect properties such as compressive strength, and even permeability when used in excess.

It can be observed in Fig. 4.3a-d that for the same sand-to-solids ratio, a larger quantity of water reduces the viscosity, while larger quantities of water and bentonite help create a more viscous paste. In the case of using a larger quantity of standardized sand, an increase in extreme viscosity values was also noted: from 31 to 154 Pa*s for minimum values, and from 448 to 1304 Pa*s for maximum values. Considering the variation of extreme values, it can be concluded that sand influences the workability of the material in its fresh state. Taking into account these aspects, the influence of standardized sand on the other analysed parameters, as well as observations during sample manufacturing, a sand-to-solids ratio of at least 2:1 provides the material with sufficient workability to be used in practice.

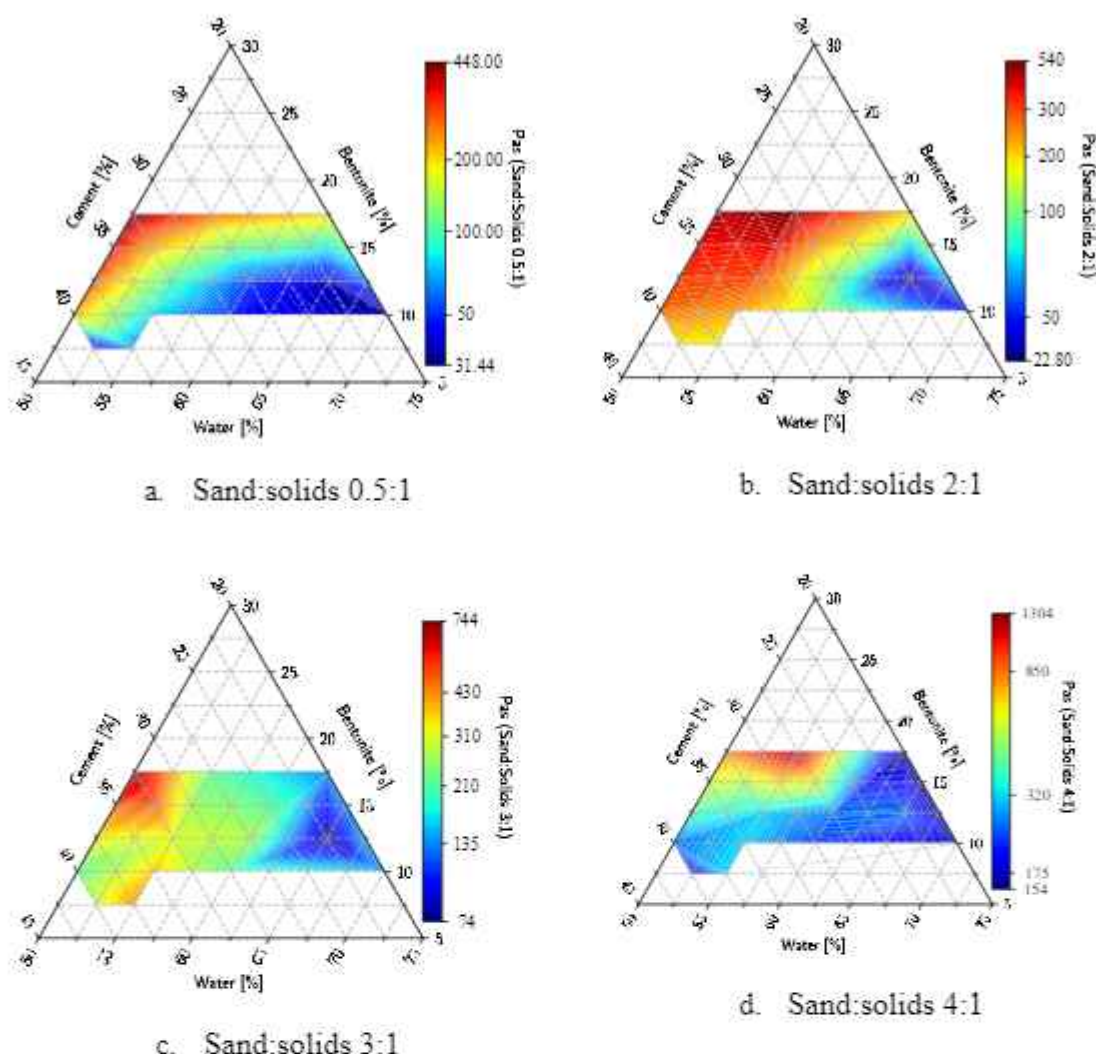


Fig. 4.3: Variation of viscosity on the study domain considering different sand to solids ratios

The reliability degree in the results obtained within the testing program was determined by calculating the coefficient of variation. The representation of the results is given in the graphs in Fig. 4.4 and Fig. 4.5. The coefficient of variation was determined as the ratio between the standard deviation and the mean values of the results obtained from tests for each standardized sand-to-solids ratio used. Thus, a low coefficient of variation indicates clustering of results around the mean value for the analysed parameter. A high coefficient of variation indicates the dispersion of results over a wider range of values.

In the case of compressive strength, it can be observed that for samples primarily governed by the quantity of cement, the coefficient of variation is significantly lower compared to samples dominated by water or bentonite. The fact that samples with higher water or bentonite content yielded a higher coefficient of variation indicates a greater spread of results under the influence of using a different quantity of standardized sand.

Regarding the permeability coefficient, for samples with higher bentonite content, a smaller variation in results was determined regardless of the quantity of standardized sand introduced into the mixture, with the opposite being true for samples with a higher cement content. Taking into account also the results presented in Fig. 4.1, the coefficient of variation of permeability is influenced by the values obtained on samples with a sand-to-solids ratio of 0.5:1. These values have an atypical spread over the studied domain due to contraction phenomena that led to cracks in the sample body. This type of phenomenon was not observed in the case of samples with sand-to-solids ratios of 2:1, 3:1, or 4:1. In the case of the initially used ratio (Fig. 4.1a), unexpected results were obtained, in the sense that reduced values of the permeability coefficient were obtained for samples with a higher cement content. It is worth mentioning that the mixture samples with a higher cement content did not crack.

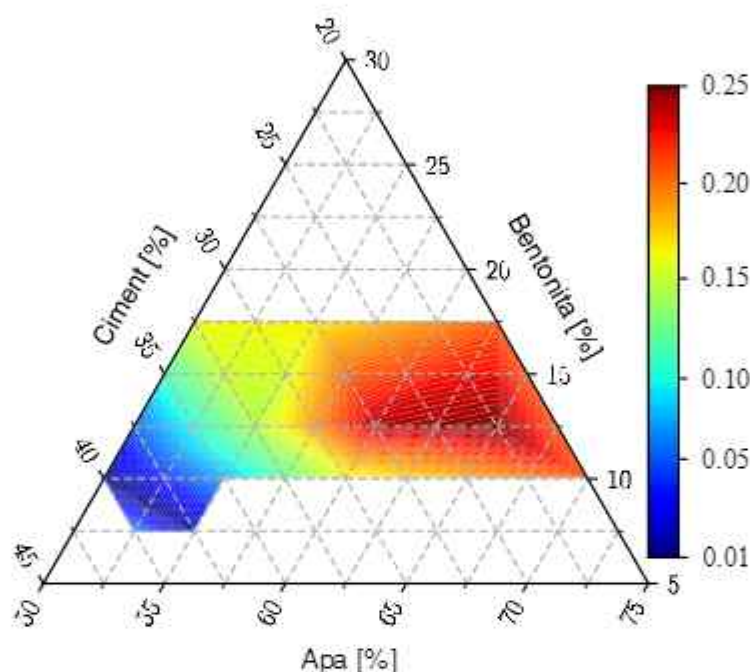


Fig. 4.4: The variation coefficient for compressive strength

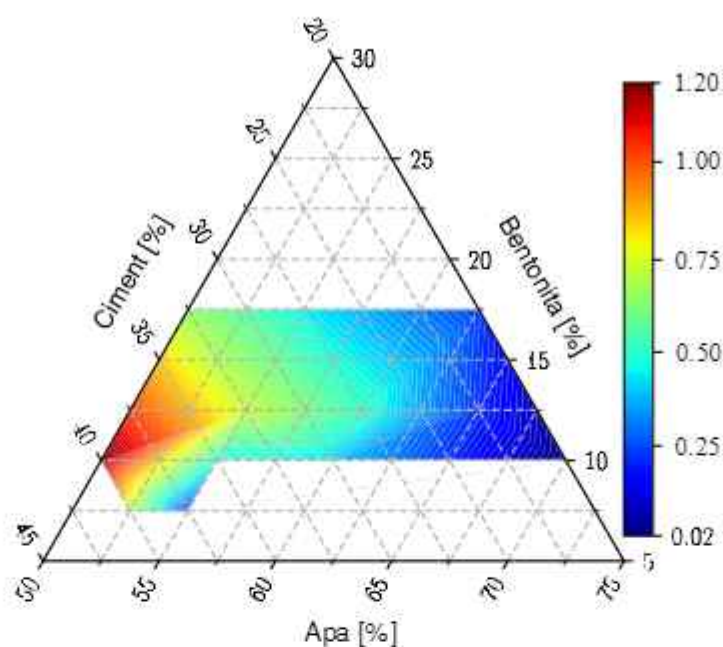


Fig. 4.5: The variation coefficient for permeability coefficient

Tab. 4: Laboratory testing results

Nr.	Water [%]	Bent. [%]	Cem [%]	Sand: solids	w/b	w/c	w/c	γ [kN/m ³]	k [m/s]	c_u [m/s]	μ [Pa*s]
1.1	50	17.5	32.5	0.50	2.86	1.54	0.54	11.84	5.94E-07	192	448.213
1.2	50	17.5	32.5	2.00	2.86	1.54	0.54	15.90	3.70E-07	232.8	469.921
1.3	50	17.5	32.5	3.00	2.86	1.54	0.54	18.18	1.41E-07	162.6	744.022
1.4	50	17.5	32.5	4.00	2.86	1.54	0.54	19.57	1.74E-07	169.8	840.025
2.1	55	17.5	27.5	0.50	3.14	2.00	0.64	10.48	5.36E-07	105.9	258.008
2.2	55	17.5	27.5	2.00	3.14	2.00	0.64	15.09	3.06E-07	144.6	540.016
2.3	55	17.5	27.5	3.00	3.14	2.00	0.64	16.71	3.55E-07	107.4	214.806
2.4	55	17.5	27.5	4.00	3.14	2.00	0.64	18.18	1.68E-07	102	1308.04
3.1	62.5	17.5	20	0.50	3.57	3.13	0.88	8.33	5.03E-07	84.6	192.006
3.2	62.5	17.5	20	2.00	3.57	3.13	0.88	12.99	5.10E-07	61.5	200.406
3.3	62.5	17.5	20	3.00	3.57	3.13	0.88	14.89	7.20E-07	99.9	134.404
3.4	62.5	17.5	20	4.00	3.57	3.13	0.88	14.09	8.06E-07	71.1	154.805
4.1	55	12.5	32.5	0.50	4.40	1.69	0.38	10.63	9.82E-07	159.3	100
4.2	55	12.5	32.5	2.00	4.40	1.69	0.38	14.77	3.33E-07	121.2	319.21
4.3	55	12.5	32.5	3.00	4.40	1.69	0.38	17.63	2.78E-07	125.7	310
4.4	55	12.5	32.5	4.00	4.40	1.69	0.38	18.78	2.96E-07	160	318.01
5.1	60	12.5	27.5	0.50	4.80	2.18	0.45	8.68	8.73E-07	96.9	50.7015
5.2	60	12.5	27.5	2.00	4.80	2.18	0.45	14.55	3.23E-07	131.7	114.003
5.3	60	12.5	27.5	3.00	4.80	2.18	0.45	16.56	3.90E-07	81.3	270.008
5.4	60	12.5	27.5	4.00	4.80	2.18	0.45	17.74	4.08E-07	80.7	259.208
6.1	65	12.5	22.5	0.50	5.20	2.89	0.56	8.20	4.18E-07	84.9	35.7011
6.2	65	12.5	22.5	2.00	5.20	2.89	0.56	13.26	5.17E-07	57.6	22.8007
6.3	65	12.5	22.5	3.00	5.20	2.89	0.56	15.38	6.34E-07	52.5	73.9224
6.4	65	12.5	22.5	4.00	5.20	2.89	0.56	16.65	3.95E-07	51.3	254.408
7.1	50	10	40	0.50	5.00	1.25	0.25	12.21	1.21E-06	1023.9	211.206
7.2	50	10	40	2.00	5.00	1.25	0.25	16.41	2.09E-07	1025.7	280.808
7.3	50	10	40	3.00	5.00	1.25	0.25	17.25	2.86E-07	1003	219.607
7.4	50	10	40	4.00	5.00	1.25	0.25	19.07	4.36E-08	1024.2	258.008
8.1	60	10	30	0.50	6.00	2.00	0.33	9.58	5.99E-07	214	47.4014
8.2	60	10	30	2.00	6.00	2.00	0.33	15.33	2.39E-07	275.7	140.404
8.3	60	10	30	3.00	6.00	2.00	0.33	17.32	3.43E-07	200.7	213.606
8.4	60	10	30	4.00	6.00	2.00	0.33	18.68	3.30E-07	198.3	228.007
9.1	70	10	20	0.50	7.00	3.50	0.50	19.15	6.80E-07	57	33.201
9.2	70	10	20	2.00	7.00	3.50	0.50	14.03	6.98E-07	50.4	35.6011
9.3	70	10	20	3.00	7.00	3.50	0.50	14.74	6.89E-07	41.4	148.804
9.4	70	10	20	4.00	7.00	3.50	0.50	16.86	6.64E-07	68.7	163.605
10.1	52.5	7.5	40	0.50	7.00	1.31	0.19	12.06	7.12E-07	1021.5	31.441
10.2	52.5	7.5	40	2.00	7.00	1.31	0.19	16.20	3.50E-07	878.1	172.805
10.3	52.5	7.5	40	3.00	7.00	1.31	0.19	17.58	2.33E-07	1023.6	288.009

Nr.	Water [%]	Bent. [%]	Cem [%]	Sand: solids	w/b	w/c	w/c	γ [kN/m ³]	k [m/s]	c_u [m/s]	μ [Pa*s]
10.4	52.5	7.5	40	4.00	7.00	1.31	0.19	18.67	1.29E-07	1022.1	174.005
11.1	55	7.5	37.5	0.50	7.33	1.47	0.20	11.24	3.95E-07	975.2	60.4018
11.2	55	7.5	37.5	2.00	7.33	1.47	0.20	16.07	3.21E-07	964.1	169.205
11.3	55	7.5	37.5	3.00	7.33	1.47	0.20	17.34	2.34E-07	993.3	429.613
11.4	55	7.5	37.5	4.00	7.33	1.47	0.20	18.37	3.03E-07	997.8	322.81

5 CONCLUSIONS

The objective of this laboratory study was to determine the sufficient quantity of standardized sand used in the preparation of water-cement-bentonite mixtures that would not influence the water retention properties and mechanical characteristics of the resulting material. Additionally, the goal was to avoid the occurrence of contraction cracks that would result from an insufficient amount of aggregate. For this purpose, 44 samples were fabricated and subjected to specific tests in the geotechnical laboratory.

The samples were prepared based on the results obtained in a study that was part of Research Report No. 2. Starting from the optimal zone determined earlier, 11 types of water-bentonite-cement mixtures were selected, with different standardized sand-to-solids ratios: 0.5:1, 2:1, 3:1, and 4:1. After completing the laboratory study, certain conclusions could be drawn.

As presented in Fig. 4.1, the hydraulic behaviour of the mixtures is improved by using a larger quantity of bentonite. Using a standardized sand-to-solids ratio greater than 1:1 is recommended as it prevents the occurrence of cracks in the sample. Additionally, using a ratio greater than 2:1 is unjustified as standardized sand does not influence the water retention capacity, and it does not interfere with the hydration process of the binder in the mix.

Analysing the coefficient of variation of permeability (see Fig. 4.5), it is noted that regardless of the quantity of sand introduced into the mix, bentonite provides consistency regarding permeability, resulting in the lowest values of this parameter. For samples primarily influenced by the quantity of cement, there is inconsistency in the results; however, these still have lower values.

The results regarding the compressive strength of the mixtures, presented in Fig. 4.2, confirm that the standardized sand does not influence the mechanical characteristics of the mixture. The graphs show that this property is governed by the quantity of cement in the mix, with a higher amount of cement resulting in higher compressive strengths. Additionally, analysing the compressive strength values for each sand-to-solids ratio reveals that the aggregate does not influence the magnitude of this parameter.

The spread of the coefficient of variation of compressive strength indicates that, regardless of the quantity of sand used, samples with a higher amount of cement yielded consistent values of this parameter, while on the opposite end, for samples with a higher amount of bentonite or water, the variation of this parameter was significantly higher.

Analysing the graphs presented in Fig. 4.3, it can be concluded that using a larger quantity of standardized sand generates higher viscosity values, thereby reducing the workability of the mixture. Another factor contributing to the improvement of this parameter is the quantity of bentonite and water, while cement does not contribute in this regard. Considering the viscosity variation values on the four graphs, it can be concluded that viscosity values for the sand-to-solids ratio of 2:1 provide sufficient workability of the mixture for proper implementation.

Therefore, considering the results obtained in the present laboratory study and the undesirable effects induced by an insufficient quantity of sand, it can be concluded that a standardized sand-to-solids ratio of 2:1 is sufficient to enhance the mixtures towards their superior characteristics, while not influencing their mechanical and hydraulic behaviour and maintaining the integrity of the samples after removing the cast. Additionally, considering factors such as the duration for the material to cure, the lengthy testing time, and the large number of samples requiring testing, starting from the 2:1 ratio, four samples will be fabricated for each type of mixture (from the eleven in the optimal zone), ensuring a higher level of reliability on the results through a statistical processing approach.

6 BIBLIOGRAPHY

- [1] D. A. Shepherd, E. Kotan și F. Dehn, „Plastic concrete for cut-off walls: A review,” *Construction and building materials*, vol. 255, 2020.
- [2] M. A. Fadaie, M. Nekooei și P. Javadi, „Effect of Dry and Saturated Bentonite on Plastic Concrete,” *KSCE Journal of Civil Engineering*, vol. 23, nr. 8, pp. 3431-3442, 2019.
- [3] Y. P. Pisheh și S. M. M. Hosseini, „Experimental Investigation of Mechanical Behavior of Plastic Concrete in Cutoff Walls,” *Journal of Materials in Civil Engineering*, 2018.
- [4] U.S. Bureau of Reclamation, Design Standards No.13: Embankment Dam, Chapter 16: Cutoff walls, U.S. Department of the Interior, 2014.
- [5] S. D. Hinchberger, J. Weck și T. Newson, „Mechanical and hydraulic characterization of plastic concrete for seepage cut-off walls,” *Canadian Geotechnical Journal*, vol. 47, nr. 4, pp. 461-471, 2010.
- [6] A. Bagheri, M. Alibabaei și M. Babaie, „Reduction in the Permeability of Plastic Concrete for Cut-off Walls through Utilization of Silica Fume,” *Construction and Building Materials*, vol. I, nr. 22, pp. 1247-1252, 2008.
- [7] European Committee of Standardization, „EN 196-1:2016: Method of testing cement - Part 1: Determination of Strength,” European Committee of Standardization, 2016.
- [8] Bega Minerale S.A., „www.begaminerale.ro,” 2021. [Interactiv]. Available: <https://begaminerale.ro/wp-content/uploads/2021/02/FT-3-Bentonita-macinata-activata-pentru-foraje.pdf>. [Accesat 12 2021].
- [9] A. Bouazza, M. Manassero și N. Smith, „Cement-Bentonite Slurry Walls for Waste Containment,” în *8th Australia New Zealand Conference on Geomechanics*, Hobart, 1999.
- [10] European Committee of Standardization, „Geotechnical Investigation and testing - Laboratory testing of soil. Part 11: Permeability tests,” European Committee of Standardization, 2014.
- [11] Asociația de Standardizare din România, „STAS 8942/6-75: Teren de fundare - Încercarea pământurilor la compresiune monoaxială,” Asociația de Standardizare din România, 1976.
- [12] European Committee of Standardization, „EN 17892-7:2017 - Geotechnical Investigation and testing - Laboratory testing of soil. Part 7: Unconfined compression test,” European Committee of Standardization, 2017.
- [13] E. K. Zavadkas și Z. Turskis, „A new logarithmic normalization method in games theory,” *Informatica*, vol. 19, nr. 2, pp. 303-314, 2008.
- [14] C.-Ș. Barbu, A.-D. Sabău, D.-M. Manoli și M.-S. Șerbulea, „Water/Cement/Bentonite Ratio Selection Method for Artificial Groundwater Barriers Made of Cutoff Walls,” *Water*, vol. 14, nr. 3, 2022.
- [15] C.-Ș. Barbu, A.-D. Sabău și A. Chirică, „Water/Cement/Bentonite Mixtures Property Testing in the Presence of Standard Sand,” în *22nd International Scientific Multidisciplinary Conference on Earth and Planetary Sciences*, Albena, 2022.