

**TECHNICAL UNIVERSITY OF CIVIL ENGINEERING
BUCHAREST**

SUMMARY OF THE PhD THESIS

ASPECTS REGARDING THE DESIGN OF CUT-OFF WALLS

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1 INTRODUCTION

The PhD thesis aims to analyse the evolution of the physico-mechanical parameters of water-bentonite-cement mixtures that form the basis for preparing injection suspensions, plastic concretes, or other materials aimed at obstructing the ground water flow.

Considering the ternary nature of the mixture, the doctoral thesis proposes the barycentric representation of its components (water-bentonite-cement). This diagram was used as a support for representing the analysed physico-mechanical properties in an intuitive manner. Due to the wide range of variation where necessary, normalized logarithmic representation of certain parameters (such as viscosity and permeability) was utilized. By using the barycentric representation, the statistical distribution of determination errors was highlighted, indicating the reliability degree in the obtained parameters, taking into account the wide variation of the analysed base values.

The variation of physico-mechanical parameters depending on the recipe constitutes important starting information for designing cut-off walls, providing limits within which design parameters can be selected, while also facilitating the preparation of quantity lists regarding the binder and bentonite consultant.

2 STATE OF THE ART

2.1 Generalities

Cut-off walls are an alternative of embedded walls that began to be used around the 1970s in the United States of America. Constructing these barriers involves excavating soil from trenches and mixing it with binders or replacing it with filling material. Depending on the size of the site, the most economical and practical way to excavate the trench is by using standard excavators or long-reach excavators, capable of reaching depths of 20m. In cases where there are limitations regarding available space, trench excavation can also utilize a clamshell bucket, commonly used in constructing diaphragm walls. The most important characteristic of bentonite barriers is their construction continuity: from start to finish, the excavation proceeds in a continuous manner, thus ensuring the two main requirements related to waterproofing and barrier size. [1]

Cut-off walls are used as means of controlling the ground water flow, both in clean environments and in contaminated ones. Additionally, such structures can be used in the construction or repair of earth dams. The mechanism of failure that can occur in earth dams is constituted by the infiltration of underground water through the base of the embankment. In this way, there is a deterioration in the values of shear parameters, causing the mass of earth to slide. By creating a watertight screen down to a theoretically impermeable layer, the flow of water that can cause the failure of the structure is stopped.

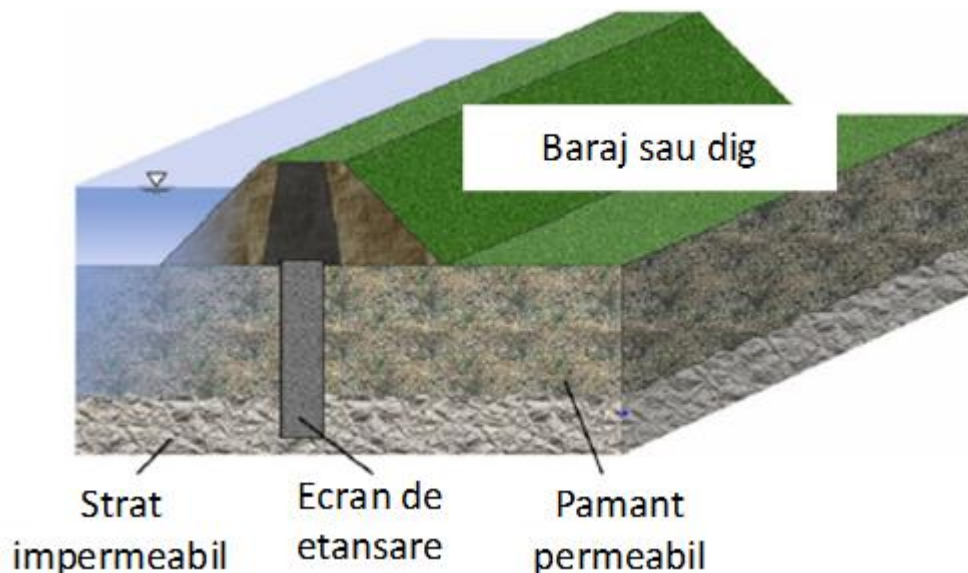


Fig. 2.1: Representation of cut-off wall in the geotechnical structure [2]

Furthermore, such structures are used for rehabilitating aging geotechnical structures that have exceeded their lifespan and require improvements to maintain their functionality. Cut-off walls represent an economical and efficient method for remediating infiltrations or for sealing contaminated sites. For the construction of barriers, depending on the geotechnical requirements generated by the site, a wide range of materials can be used.

2.2 Plastic concrete

According to current European standards, plastic concrete is defined as a material with low strength, low modulus of elasticity, capable of supporting larger strains than normal concrete. Typically, a small amount of cement is introduced into the composition of this concrete, and a high water-cement ratio is used. Additionally, the mixture may contain bentonite and/or other materials such as fly ash and other additives. This type of concrete must be produced according to special design specifications to meet the requirements of permeability, deformability, and workability. For plastic concrete, there is no limitation on the water-cement ratio. [25]

The American standard defines plastic concrete as a variation of traditional concrete, in which bentonite partially replaces cement. Plastic concrete was primarily developed for use in constructing dikes or in soft soils, where higher deformability is required due to settlements or bending, and where strength is not the primary design requirement. [10]

This type of material is also used in areas where seismic activity is present due to its capacity to absorb tensile forces induced by ground movements. The use of this type of concrete involves careful selection of the recipe in terms of the quantities of materials in the mix, their characteristics, but also requires a rigorous laboratory testing program to determine the physico-mechanical properties of the mixture and alternative solutions for optimizing the chosen solution. Additionally, for execution control and verification of calculation hypotheses, in-situ tests can be carried out to attest to the quality of the works.

Plastic concrete cut-off walls can be constructed using technologies similar to those used for constructing diaphragm walls. The trench is excavated using machinery equipped with heavy rods at the end of which is a hydraulic clamshell bucket or through the use of hydro-excavators. To ensure the stability of the trench walls, bentonite slurry is used, thereby preventing their collapse. The next step involves pouring the plastic concrete. Concrete is poured using concrete chutes, starting from the bottom of the trench, thus avoiding material segregation.

Plastic concrete is thus characterized by its ability to deform under load, which is advantageous when ductility is required or when tensile forces generated by uneven loading along the wall or seismic activity are estimated. Additionally, another advantage is the lower probability of material yielding or cracking, which would result in increased permeability. [26]

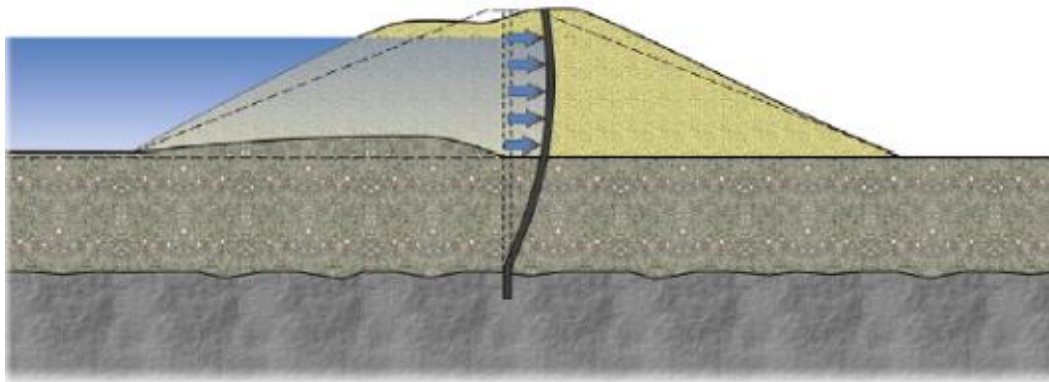


Fig. 2.2: Representation of a cut-off wall made of plastic concrete [26]

2.2.1 Material mix

The recipe for this type of concrete is similar to that for traditional concrete. The additional element is bentonite, which is added to improve both the permeability and ductility of the screen. Depending on the specifications of each project, it is possible to vary the ratio between the materials used in the mix. In addition to the basic materials (cement, bentonite, water, sand, or gravel), additives can be used to improve the workability of the material or to delay its setting time.

2.2.1.1 Cementul

Cement is a hydraulic binder, namely a finely ground inorganic material that, when mixed with water, forms a paste that sets and hardens due to hydration reactions and processes, maintaining its strength and stability even underwater after hardening. Properly dosed cement mixed with aggregates and water should be capable of producing concrete or mortar that maintains its workability for a sufficient period of time and, after well-defined periods, should achieve specified strength levels. Cements are composed of various materials and are statistically homogeneous in composition as a result of ensuring the quality of production and handling processes. [27]

2.2.1.2 Mineral aggregates

In order to obtain a suitable particle size distribution curve for the concrete recipe, the following factors should be taken into account:

- Aggregate shape: Rounded aggregates are preferable over angular ones in terms of concrete flow;
- Aggregate size: Larger aggregates offer high workability but increase the risk of segregation;
- Proportion of fine material: Using a larger quantity of this type of material can result in a more viscous mix and compromise concrete workability due to the need for a larger volume of water, which, consequently, would require a higher dosage of additives [30]

Aggregates play a crucial role in the material mix for obtaining plastic concrete. By selecting appropriate sizes, the tendency for concrete segregation can be reduced. The workability of the material can be improved by using rounded aggregates sourced from river basins and by limiting the aggregate size to 25.4mm (1 inch). The ratio between coarse and fine aggregates has an impact on both the density and the strength of the wall. Typically, a 1:1 ratio is used. [10]

The Austrian standard ONORM B4452 limits the maximum aggregate size to 22mm but notes that the use of particles larger than 16mm is rare. Additionally, it is mentioned that special attention must be given to the risk of segregation and deformability of plastic concrete when the maximum aggregate size exceeds 8mm. The proportion of fine particles must be chosen to ensure the workability of the material. [31] [2]. In reference papers there were used aggregates with dimensions of 12 mm, [32], $4.75 \div 9.50$, $9.5 \div 19.00$ mm [4] [33], up to 20.00mm. [34]

2.2.1.3 Bentonite

Bentonite is a term used for materials originating from natural clay and composed mainly of the clay mineral called montmorillonite. [35] Bentonite refers to any material consisting of minerals belonging to the smectite group, and its properties are dictated by this type of minerals. The characteristics of the smectite mineral group are: high cation exchange capacity, large specific surface area, high swelling potential, and reduced permeability. [36]

The most commonly encountered types of bentonites are sodium-based or calcium-based, characterized by the type of external cation adsorbed on the clay particle surface during the mineral formation process or, in the case of treated bentonite, during processing. Sodium bentonite is used more frequently than calcium bentonite due to its superior swelling capacity and reduced permeability. [37] [38]. Even though calcium bentonite has a lower swelling capacity and higher permeability, some researchers have suggested that it may be more stable than sodium bentonite when exposed to chemical compounds in fluids. [36].

In the case of plastic concrete, the bentonite in the composition acts as a stabilizing agent and prevents concrete segregation, creating a homogeneous mixture. The properties of bentonite include plasticity and ion exchange capacity, which contribute to the uniform molecular arrangement of the mixture, increasing plasticity and reducing permeability [39]. Bentonite has a swelling potential of up to 300% after mixing with water, a property that makes saturated bentonite usable in plastic concrete execution to eliminate the negative effects of high-water absorption when using dry bentonite. [40]. To saturate bentonite, the water-bentonite ratio should be at least 3, and saturation should be carried out at least 24 hours before producing plastic concrete. The bentonite-water mixture should be made using special blades to ensure complete saturation and paste homogeneity. [41].

2.2.2 *Mixing procedure*

One of the methods of mixing the components of plastic concrete involves initially hydrating the bentonite for a period of up to 24 hours. After this time, the cement is added, followed by the aggregates. [2] [4] [5] [32]. Another procedure involves pre-hydrating the bentonite with a portion of the water used in the mixture before introducing the other components. Additionally, it's possible to hydrate the bentonite for a duration of 8 hours and then add a dry mixture of aggregates and cement. The different mixing procedures result in differences in mechanical properties as well as permeability coefficient values. The hydration of bentonite depends not only on the type of bentonite but also on the method and equipment used in creating the mixture. [2]

The mixture of materials can also be done under dry conditions, thus eliminating the need for pre-hydration of the bentonite. This method presents two important aspects:

- As soon as water is introduced into the mixture, the paste must be immediately mixed to ensure hydration of the bentonite and homogeneity of the mixture;
- The quantity of dry bentonite must be carefully controlled and introduced slowly into the mixture to allow sufficient time for water absorption. The entire quantity of bentonite should not be added at once to avoid the formation of accumulations of unsaturated material, which would lead to the creation of an inefficient material. [41]

The benefit of using dry bentonite lies in saving time and removing technological impediments, as there is no longer a need for hydration and prior storage of bentonite slurry for up to 24 hours. As discovered in previous studies, the compressive and tensile strength of plastic concrete remains the same regardless of whether the bentonite used has been hydrated or not. Moreover, for longer maturity periods, the differences become negligible. However, slightly higher permeability values have been recorded for plastic concrete where dry bentonite was used. [41]

2.2.3 *Laboratory testing for determining of physical and mechanical characteristics*

The correct use of a material with the functions held by plastic concrete involves determining a series of physical and mechanical parameters to ensure performance requirements during the design phase. The properties of plastic concrete can be adapted according to site conditions and structural requirements that need to be met.

2.2.3.1 *Unconfined compression test*

Characterizing plastic concrete can begin with unconfined compression testing. According to concrete production standards, the water-cement ratio is an important factor in determining the material class and thus the compressive strength: as the water-cement ratio decreases, an increase in compressive strength is observed. [42]

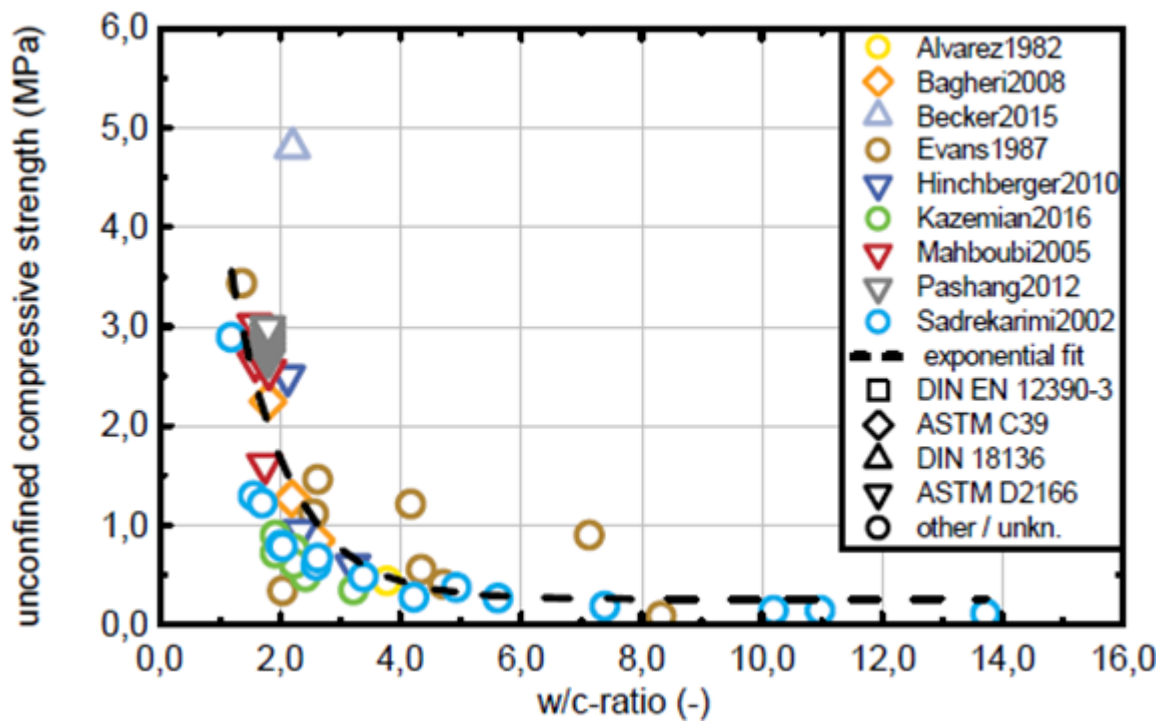


Fig. 2.3: Representation of unconfined compression tests met in reference papers [2]

Fig. 2.3 presents the results of various research studies on uniaxial compression tests on different recipes of plastic concrete, matured at 28 days. As known in the case of concretes, it can be observed that with the increase in the water-cement ratio, there is a decrease in the compressive strength of the material, although the influence of bentonite results in a modification of the water availability in the mixture to hydrate the cement. In other words, the compressive strength of plastic concrete decreases with the increase in the water-cement ratio, but the overall behaviour is also governed by the quantity of bentonite.

2.2.3.2 Triaxial compression test

In the specialized literature, studies have been conducted including triaxial compression tests on various recipes of plastic concrete. Triaxial compression tests aim to highlight the stress-strain relationship under static conditions with certain applied stresses.

The tests made were of CU type (consolidated-undrained) [32] [33] or CD-type (consolidated-drained) [43]. Prior to determining the failure parameters of the samples, they were saturated, thus determining the coefficient of permeability. The samples used were prepared similarly to soil samples: the samples had a height-to-diameter ratio equal to 2, were protected by a membrane, and had porous stones at both ends. During the tests, both the applied stresses and resulting deformations were measured, as well as the pore water pressure.

The influence of cell pressure on the tested specimens was observed. An increase in both the modulus of elasticity and the compressive strength of the specimens was noted as the pressure at which the test was conducted increased. [43]. Additionally, the failure mechanism of the sample is influenced by the consolidation pressure. Specimens tested at low pressure exhibit brittle behaviour at yield, while for higher consolidation pressures, the behaviour of the specimens is ductile, with the material showing elongations up to 8-9% greater for failure stresses. [33]

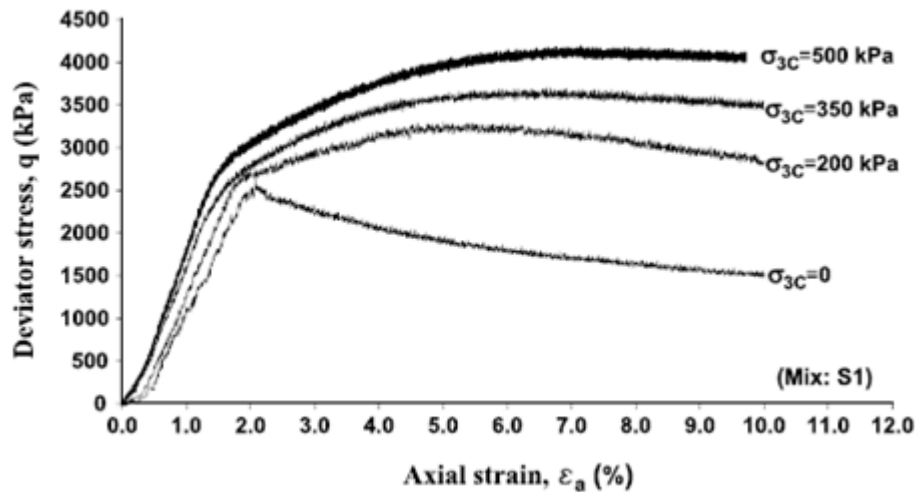


Fig. 2.4: Rezultatele încercării de compresiune triaxială la diferite eforturi radiale [33]

Increasing the bentonite content, the peak and slope of the linear part of the stress-strain curve become smaller. This is due to the role of bentonite in weakening the bonds formed between cement particles and aggregates, also reducing the hydration rate of the cement in the sample. Thus, the compressive strength and elastic modulus of the plastic concrete increase with the amount of cement introduced into the mix or decrease depending on the amount of bentonite. [43] [44]

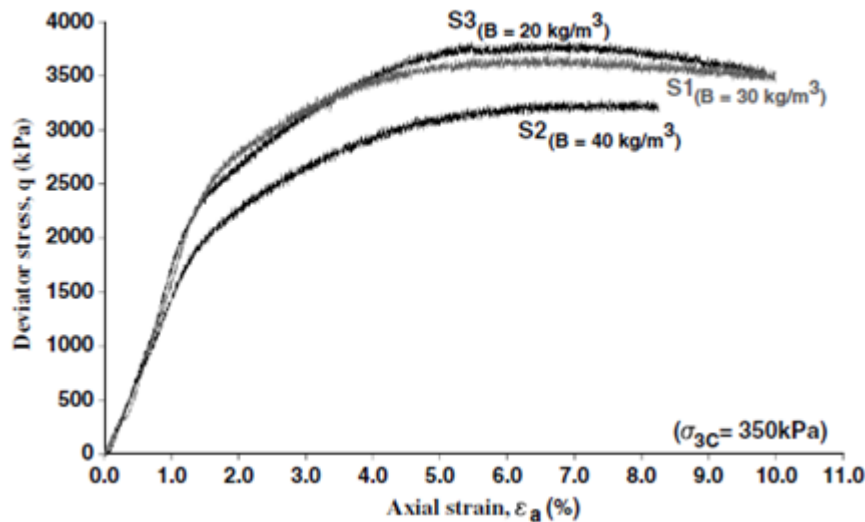


Fig. 2.5: Representation of the influence of bentonite content on mechanical behaviour

2.2.3.3 Hydraulic conductivity

The purpose of plastic concrete structures is to ensure the sealing of contaminated sites, stop or divert groundwater flow, or remediate infiltrations at the level of dikes or earthen dams. Thus, considering the functionalities of the structures, the characteristic of utmost importance is constituted by the hydraulic behaviour of the material

The permeability of concrete is closely connected to the porosity of the material (the size and distribution of pores) and the water-to-cement ratio used in the manufacturing of concrete.

To meet specific requirements for ensuring impermeability, it's important to minimize the water-to-cement ratio used in the mix while maintaining the concrete's consistency requirements. In practice, to achieve a certain degree of concrete impermeability, control over its strength class is also necessary, in correlation with minimizing the water-to-cement ratio as much as possible. The water-to-cement ratio considered in the composition design must satisfy the concrete's requirements regarding strength class, durability, and impermeability grade. [45]

The permeability of materials like plastic concrete is higher than that of traditional concrete. In cases where a low modulus of elasticity and low permeability of the material are required, satisfying both criteria are challenging. Due to the high values of the water-cement ratio, the permeability of the mixes is high. The permeability coefficient values of plastic concrete range between 10^{-8} to 10^{-10} m/s. [4] [9].

Considering the low compressive strength and permeability coefficient values, plastic concrete can be subjected to geotechnical tests. In Fig. 2.6 results from literature are presented correlating permeability coefficient values with the compressive strength of plastic concrete.

The permeability coefficient of plastic concrete samples increases as the compressive strength decreases. This phenomenon can be attributed to a higher porosity of the material, which increases with the increase of the water-cement ratio, consequently reducing the compressive strength. [2]

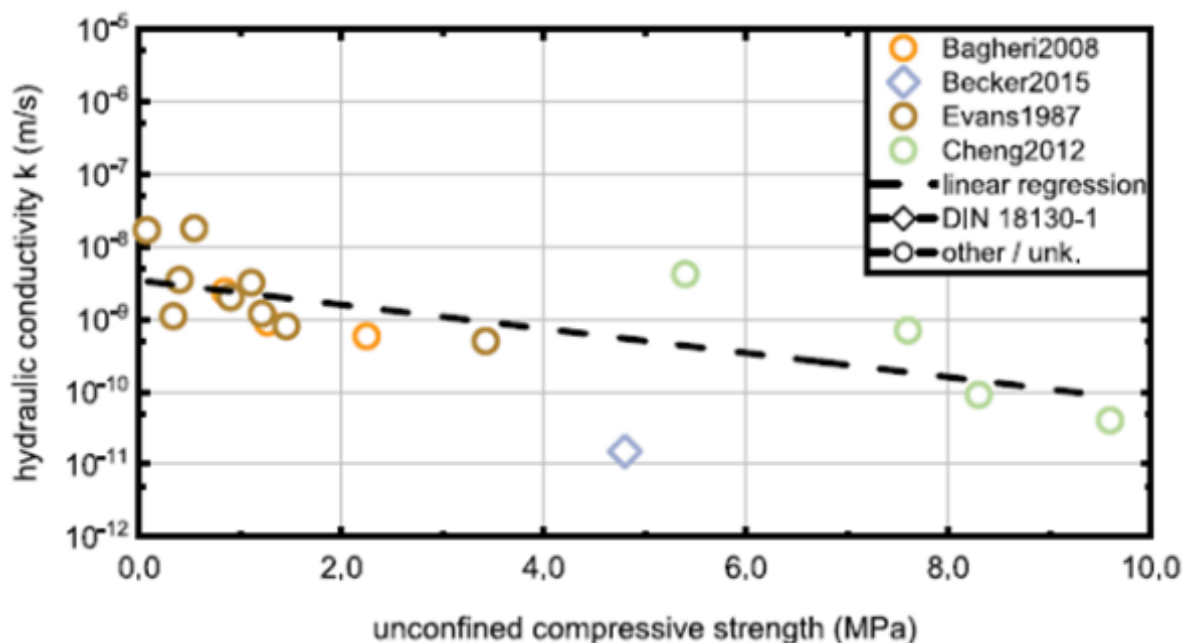


Fig. 2.6: Variation of permeability coefficient function of the compressive strength of the plastic concrete [2]

3 THE ANALYSIS OF WATER-CEMENT-BENTONITE RATIO

In the reference papers, various authors have used varied ratios between the constituent elements of the mixtures for specimen fabrication. These values formed the basis of the current laboratory study. The study attempted to cover a wide range of variations in material ratios while considering the significant influence that the quantity of bentonite has on compressive strength and water retention capacity (as demonstrated in the current laboratory study). Therefore, the proportion of bentonite used in plastic concrete mixtures was limited to 30%.

Tab. 1: Ratios between the materials of the mixtures, extracted from reference papers

Reference papers	Water-cement ratio	Water-bentonite ratio	Bentonite-cement ratio
This paper	1.25÷3.65	2.00÷10.40	0.175÷1.25
Shepherd et al, 2020 [26]	3.30÷10.00	-	0.10÷0.24
Fadaie et al, 2019 [41]	1.60÷2.00	8.00÷20.00	0÷0.40
Pisheh et al, 2018 [33]	1.80	6.30÷10.20	0.14÷0.29
US Dept. of Interior, 2014 [10]	1.00÷2.78	6.67÷13.90	0.10÷0.22
Hinchberger et al, 2010 [32]	1.70÷2.35	12.50÷18.20	0.20÷0.30
Bagheri et al, 2008 [4]	1.80÷2.60	13.00	0.14÷0.23

3.1 The objectives of the research

This study proposes a different approach regarding the evaluation of the physical-mechanical properties (viscosity, permeability, compressive strength) of plastic concrete and the graphical representation of the percentage proportions of the component materials. The representation of the mixtures is done on a subdomain of a ternary diagram where the components are expressed as percentages. The material properties (viscosity, permeability, and compressive strength) are presented as nodes on a grid corresponding to possible mixtures.

The present study involves the fabrication and laboratory testing of 52 plastic concrete specimens in a geotechnical laboratory. The behaviour of this material is primarily governed by the relationship between the water-bentonite-cement content. To prevent cracking of the material, standardized sand described in EN 196-1 - Methods of testing cement, was used in a 1:1 ratio with the solid part of the mixture (bentonite and cement).

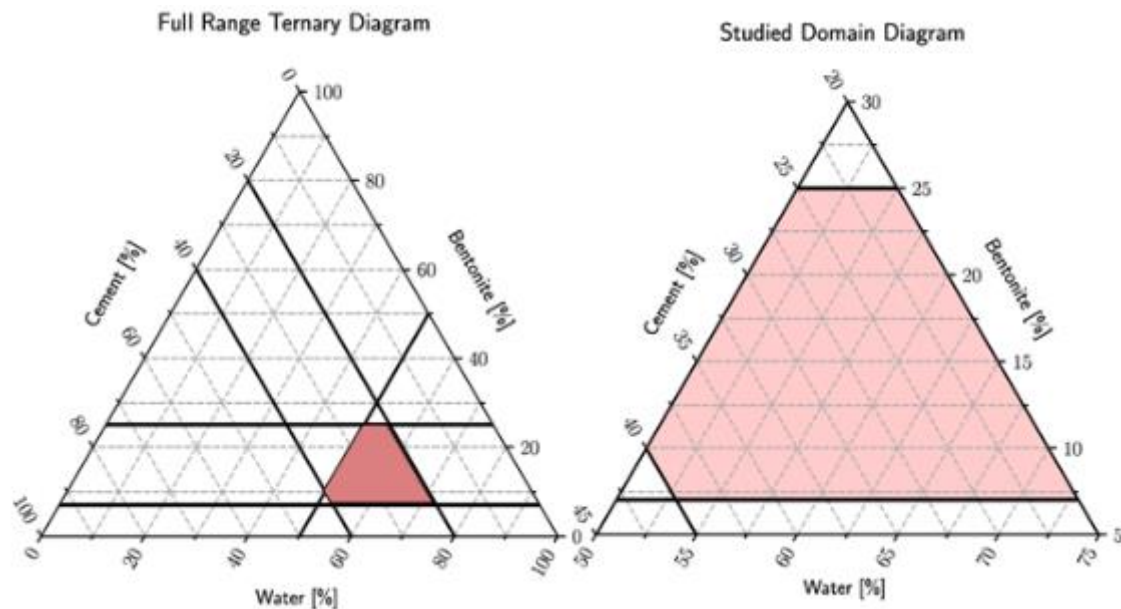


Fig. 3.1: Restrângerea domeniului de interes pentru realizarea studiului

3.2 Manufacturing of the samples and testing methods

3.2.1 Components of the mixture

For the preparation of the specimens, high early strength Portland cement was used, with a compressive strength of 42.5 MPa (CEM IIA 42.5R). The cement used in specimen fabrication was not admixed or enhanced for performance improvement. Sodic bentonite was used for specimen fabrication, typically employed in drilling fluid preparation. Sodic bentonite has the capacity to increase the viscosity of drilling fluid and possesses waterproofing properties. According to the recommendations of the EN 196-1:2016 standard regarding cement testing methods, standardized sand was used for specimen preparation.

Apart from this type of sand, aggregates of different nature or sizes were not used. The use of sand was motivated by the attempt to prevent cracking of the specimens during the hydration process of plastic concrete. In the recipe of each mixture, the sand-to-hydraulic binder ratio (cement and bentonite) was 1:1. Although sand influences the overall behavior of plastic concrete, the relationship between the quantity of sand and that of bentonite and cement is bijective. Furthermore, in a 4D barycentric representation, due to linear variation, the quantity of sand creates a plane.

3.2.2 Manufacturing the samples

Following the study of specialized literature, three options for obtaining the mixture of components were identified. One of them, more commonly encountered, involves the pre-hydration of bentonite 24 hours before adding the cement and aggregates. [2] [4] [5] [32]. Another possibility involves pre-hydrating the bentonite with a portion of the total amount of water used in the mixture and then introducing the other components. The last option is mixing the dry components (cement, bentonite, and sand) and then adding water.

According to a study, the performance of plastic concrete regarding permeability and compressive strength is not affected by whether the bentonite was pre-hydrated or not. Moreover, for longer periods of time after reaching material maturity, the differences become negligible. [41]

After weighing each component, the dry mixture was prepared so that the materials were evenly distributed. In case the bentonite was not distributed throughout the entire mixture mass, there was a possibility that, upon adding water, material accumulations could form, leading to the creation of a heterogeneous mixture with concentrations of unhydrated zones. The uneven distribution of the mixture affects both the specimen fabrication procedure (segregation zones or cavities) and the material performance. Following the proper preparation of the solid mixture, the required amount of water was added. Subsequently, the mixture was mixed until a paste of uniform consistency was obtained. The resulting material was poured into cylindrical plastic molds with a diameter of 50mm and a height of 100mm, suitable for the subsequent testing of the material in the triaxial compression apparatus. Prior to pouring the material, a thin layer of technical oil was applied inside the molds to facilitate easy demolding of the plastic concrete. The testing program of the specimens commenced after 28 days from their fabrication, allowing the manufactured material to reach its class.

For extreme values of each component, unfavourable behaviour was observed, indicating the need to expand the range of values. Excessive bentonite content led to the production of a crumbly material, while a higher quantity of cement reduced the workability of the mixture. A high water content caused cracking of the specimens and sedimentation of aggregates, despite ensuring a high workability of the material.

3.2.3 Viscosity

The determination of viscosity was performed immediately after pouring the plastic concrete into cylindrical molds. This test was conducted using a rotational viscometer, specifically the Haake Viscotester 7 Plus. The viscometer measures the resistance of the mixture to rotational spindles, which can have different geometries (chosen based on the consistency of the tested material). The resistance obtained dictates the viscosity of the mixture. Considering the tested paste as a quasi-Newtonian fluid, the dynamic viscosity of the material is determined from the slope of the shear stress-shear rate (τ - $\dot{\gamma}$) curve.

The fresh plastic concrete specimen was tested using the dynamic viscometer. Several spindle rotation speeds were used during the test, ranging from 0.1 rpm to 100 rpm. The viscosity value was chosen based on the measurement confidence level indicated by the apparatus. It was preferred to use the values of the initial test steps due to the susceptibility of some specimens to settling immediately after pouring into the cylindrical molds.

3.2.4 Permeability coefficient

The coefficient of permeability of the plastic concrete specimens was determined using the constant gradient method in a triaxial compression apparatus. The coefficient of permeability represents the ratio of the filtration velocity v to the hydraulic gradient under which the flow occurs.

The permeability test using the constant gradient method is conducted by applying a water flow through the specimen 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 specimen against gravity, from bottom to top, at a constant pressure of 280 kPa. During the test, the volume of water introduced was continuously measured. The volume of water evacuated was recorded using a digital volume controller.

3.2.5 Compressive strength

The compressive 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 specimen. The unconfined compressive strength was determined following the guidelines of STAS 8942/6-72: Foundation soils - Uniaxial compression test of soils, and EN 17892-7:2018 - Unconfined compression test.

According to STAS 8942/6-76, the unconfined compressive test consists of continuously applying axial loading to the specimen to achieve:

- p_c unconfined compressive strength;
- ϵ , specific axial strain. [55]

The unconfined compressive strength test can be done in two ways:

- with constant speed and measuring the resulting stresses;
- with imposed efforts and measuring the resulting axial strains. [55]

3.3 Test results

The viscosity of the fresh material was measured using a rotational viscometer. The dynamic viscosity of the mixture results from the slope of the τ - γ' curve, assuming it is quasi-Newtonian. The viscosity variation is significant, ranging from 0.68 to 401.87 Pa*s.. In Fig. 3.2 the variation of viscosity across the studied range is presented. This representation can be used to assess the workability of the mixture in its fresh state. It can be observed that by limiting the viscosity to 5 Pas, segregation is prevented. The workability of concrete in its fresh state is considered acceptable for values up to 100 Pas, although an ideal behaviour would be characterized by approximately 50 Pa*s. To enhance workability, superplasticizer additives can be introduced into the mixture.

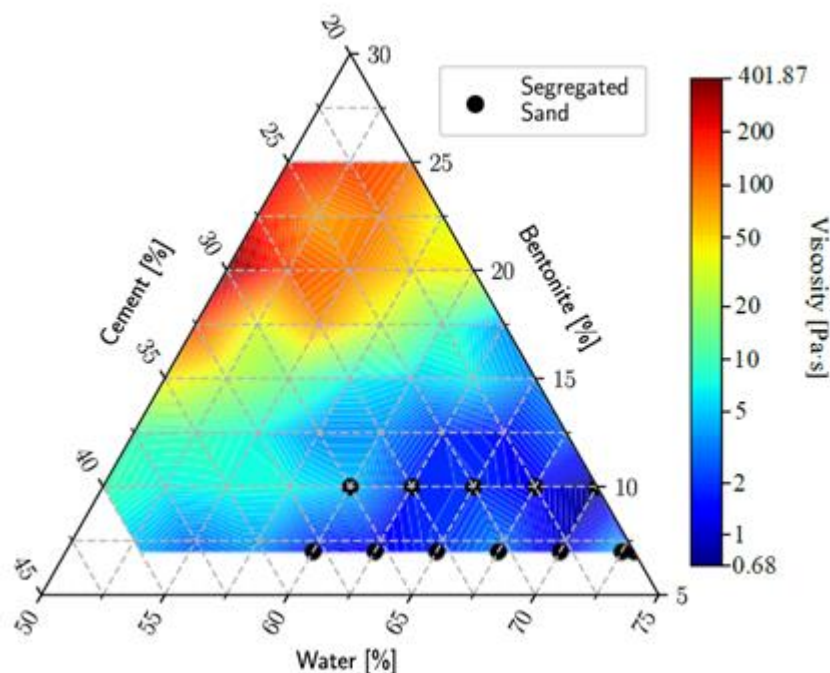


Fig. 3.2: Variation of viscosity on the study domain

In Fig. 3.3 it is noted that the compressive strength of plastic concrete is negatively affected by a bentonite content exceeding 17%, with the difference in values being at least double compared to specimens with a higher cement content. Additionally, after conducting the tests, this limit of bentonite content also dictated the yielding mechanism of the material, with specimens containing more than 17% bentonite behaving similarly to soil, while the remaining specimens exhibited behaviour similar to weak concrete.

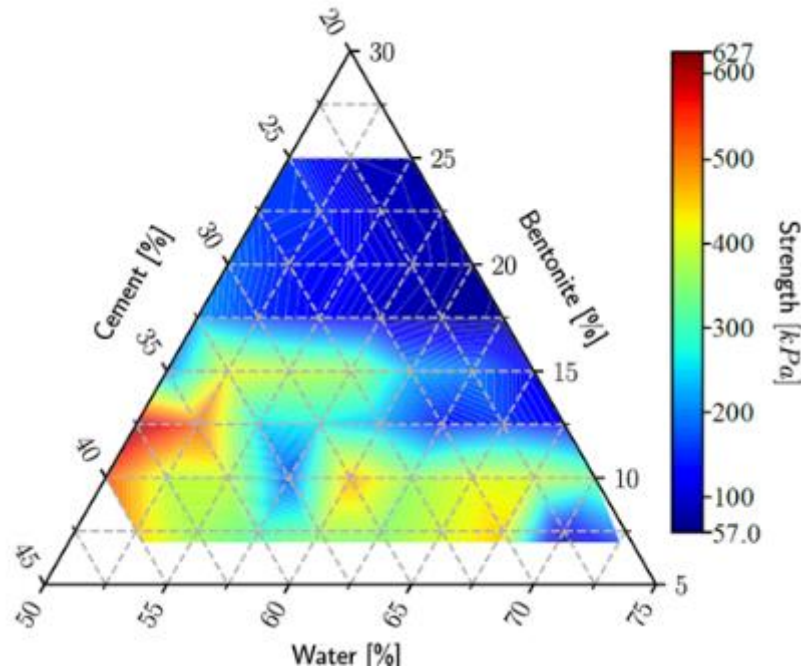


Fig. 3.3: Variation of the compressive strength on the study domain

In Fig. 3.4 depicting the variation of the permeability coefficient, the same limit of approximately 17% bentonite content indicates a change in the hydraulic behaviour of plastic concrete. On the graph, a decrease of up to 5 times in the value of the permeability coefficient can be observed around this separation zone.

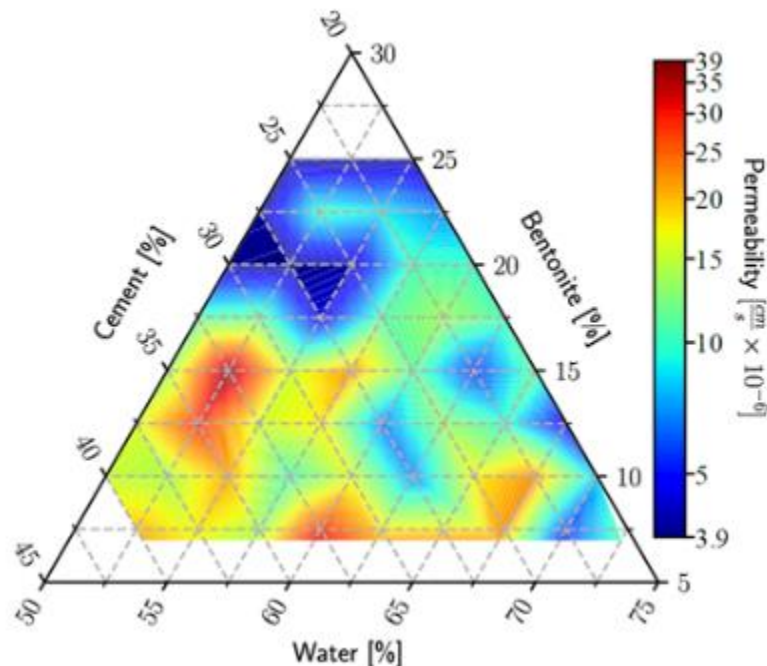


Fig. 3.4: Permeability coefficient variation on the study domain

By increasing the quantity of bentonite used in manufacturing the plastic concrete (points marked with yellow in Fig. 3.5) generate a less inferior compressive strength (5 times weaker) with respect to the samples in which the governing material is cement. On the other hand, the viscosity reaches values up to 1.5 times higher than those measured for the other specimens. The variation in compressive strength of this material has been documented in specialized literature. [32] [34] [44], the existing information confirms the results obtained in the laboratory study.

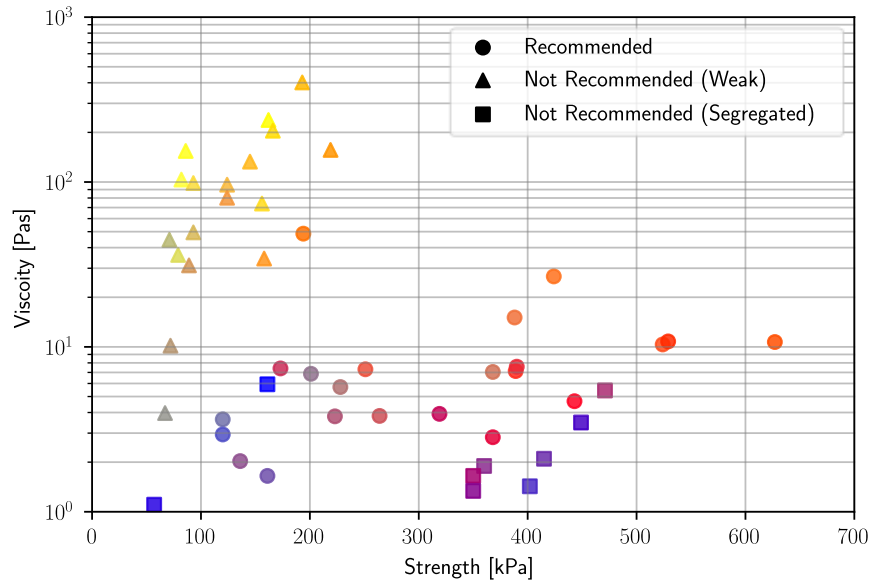


Fig. 3.5: Test results – viscosity vs compressive strength

In Fig. 3.6 and Fig. 3.7 the variation of compressive strength is presented as a function of the quantitative water-cement ratios and water-bentonite ratios, respectively. In both cases, the influence of the third component on the material behaviour is highlighted. In Fig. 3.6 specimens with a bentonite content exceeding 17.5% are marked in yellow, and the compressive strength values are limited to approximately 200 kPa. This phenomenon is caused by the ability of bentonite to weaken the cementitious bonds. In Fig. 3.7, samples dominated by the presence of bentonite are characterized by a water-bentonite ratio of less than 4. Mixtures governed by the presence of bentonite are grouped in both representations, suggesting its negative influence on compressive strength.

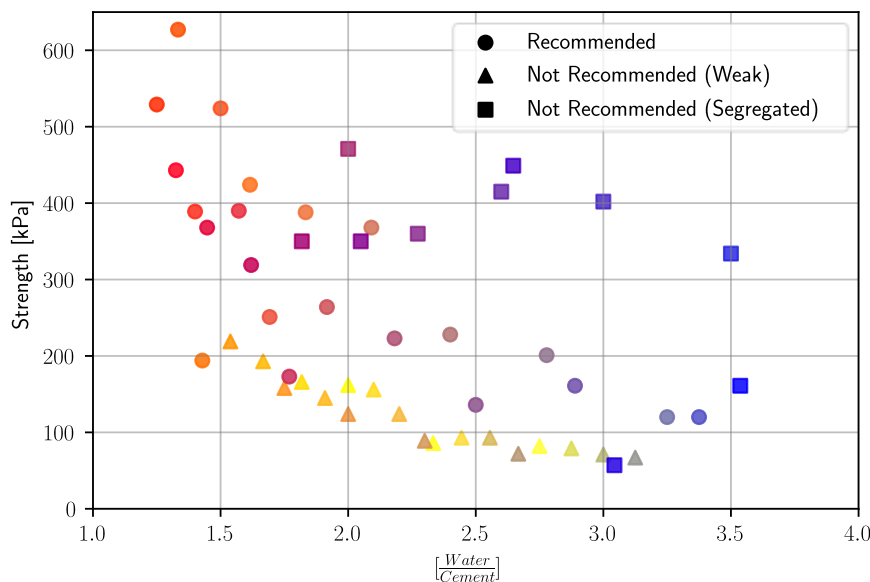


Fig. 3.6: Variation of compressive strength function of the water-cement ratio

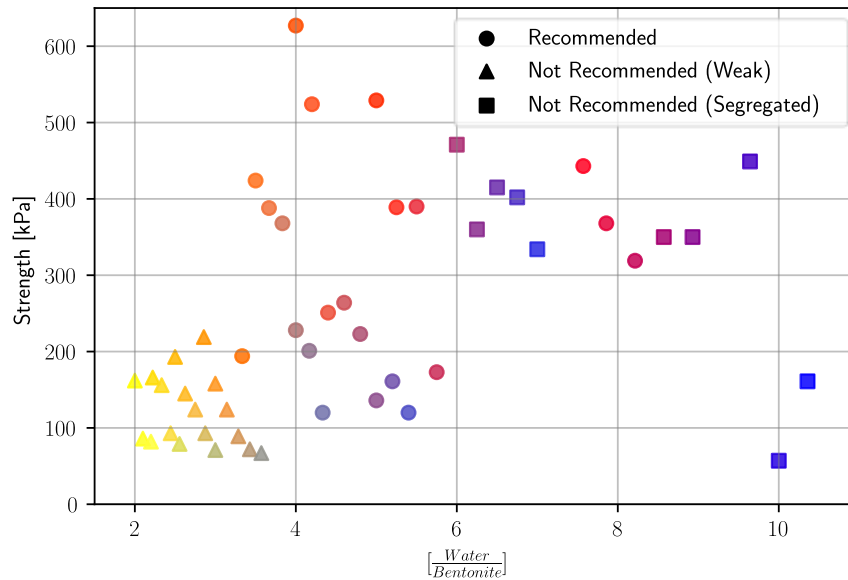


Fig. 3.7: Variation of compressive strength function of the water-bentonite ratio

Besides generating a more viscous mixture, a larger quantity of bentonite equally negatively impacts cementitious bonds. Thus, excessive use of bentonite affects the compressive strength of plastic concrete. Moreover, excessive use of bentonite not only fails to reduce the material's permeability coefficient but also affects it more drastically. This phenomenon arises from the need for a larger quantity of water for bentonite hydration. Using a larger quantity of water results in excessive porosity of plastic concrete. The variation of viscosity concerning water-cement and water-bentonite ratios is presented in Fig. 3.8 and Fig. 3.9. These representations highlight how the viscosity of the material in its fresh state is influenced by the water and bentonite content of the mixture.

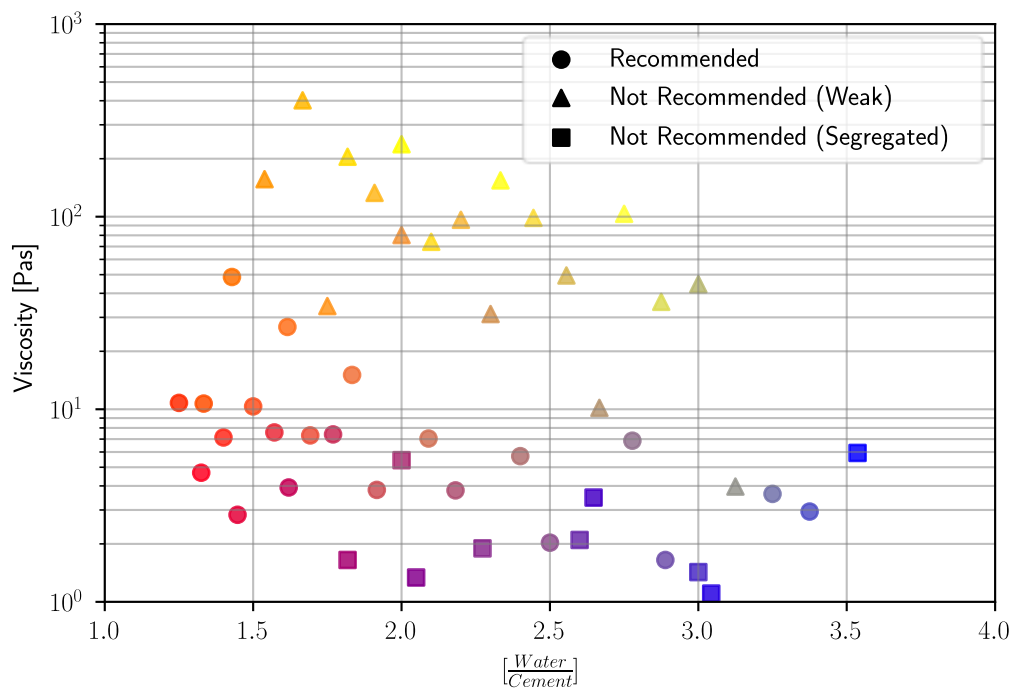


Fig. 3.8: Variation of viscosity function of the water-cement ratio

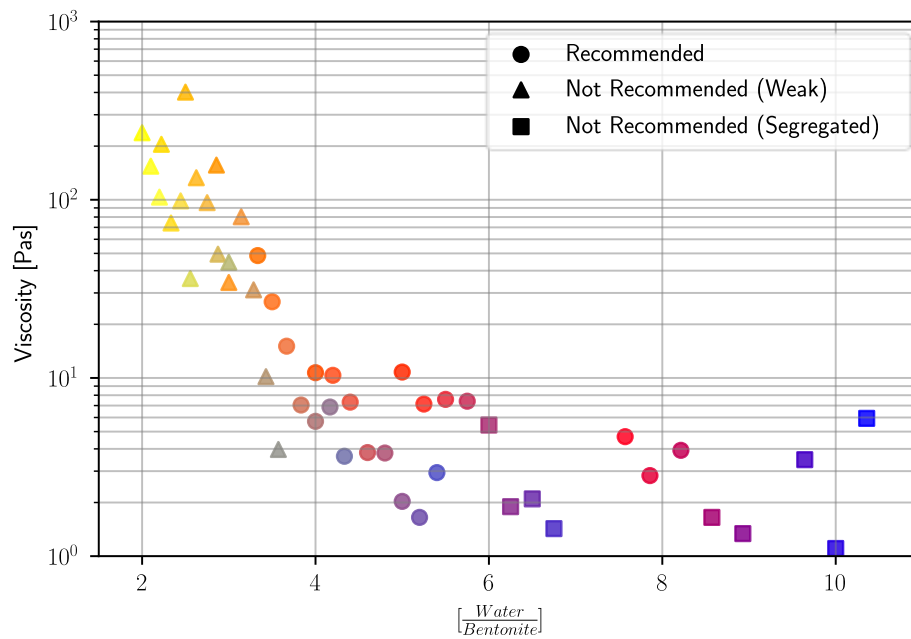


Fig. 3.9: Variation of viscosity function of the water-bentonite ratio

3.4 Conclusion of the first testing stage

The laboratory study was influenced by factors such as the magnitude of the studied domain, the large number of specimens tested, the duration of the testing periods, and the time interval required for the plastic concrete specimens to reach maturity. For these reasons, only one specimen was fabricated for each mixture. Consequently, there is a possibility that some results may lack sufficient accuracy. Despite this, the results obtained in this initial laboratory study allow for the narrowing down of the study domain (see Fig. 3.10). The specimens fabricated in the second part of the research were chosen from the narrowed study domain presented in Fig. 3.10.

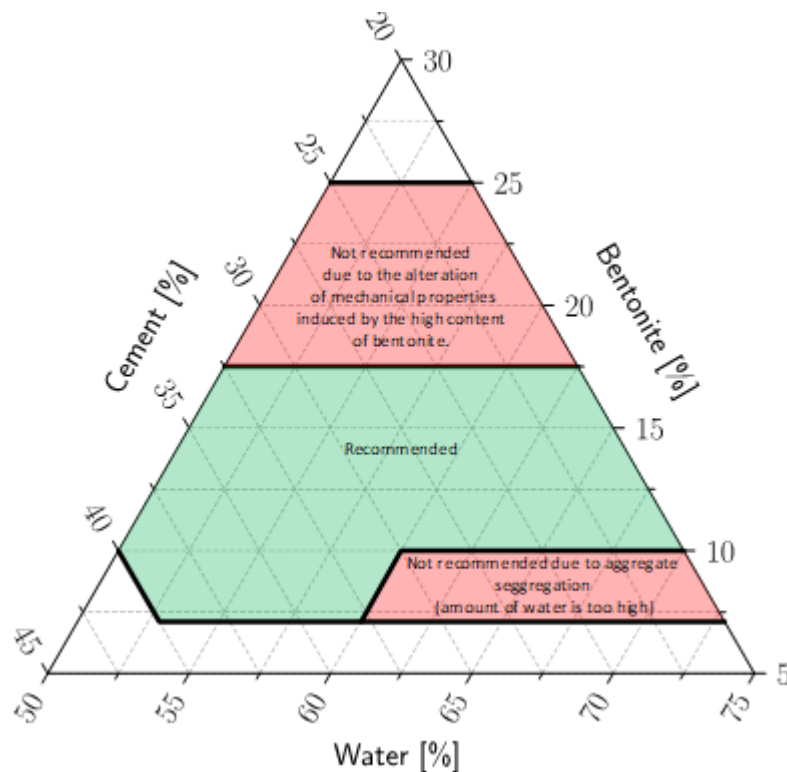


Fig. 3.10: Restriction of the study domain based on the test results

4 THE STUDY OF STANDARDIZED SAND QUANTITY ADDED IN WATER-CEMENT-BENTONITE MIXTURES

4.1 Objectives of the study

The objective set for the second laboratory study is to determine the sufficient quantity of standardized sand in the mixture to prevent the consequences of shrinkage and hydration phenomena of the binder, while simultaneously not affecting the mechanical properties and water retention of the mixture. To determine the influence of the amount of sand on the mixture, four standardized sand-to-solid ratios were used, ranging from 0.5:1 to 4:1. Using the 0.5:1 ratio, the amount of sand used in the first part of the study was halved, thus covering the lower limit of the amount of sand that could be used for the mixture. Therefore, on the optimal surface of the ternary diagram, eleven water-cement-bentonite mixtures were chosen, also made in the first part of the study. For the selected mixtures, 4 specimens were fabricated, differing by the standardized sand-to-solid ratio used: 0.5:1, 2:1, 3:1, and 4:1. (Fig. 4.1).

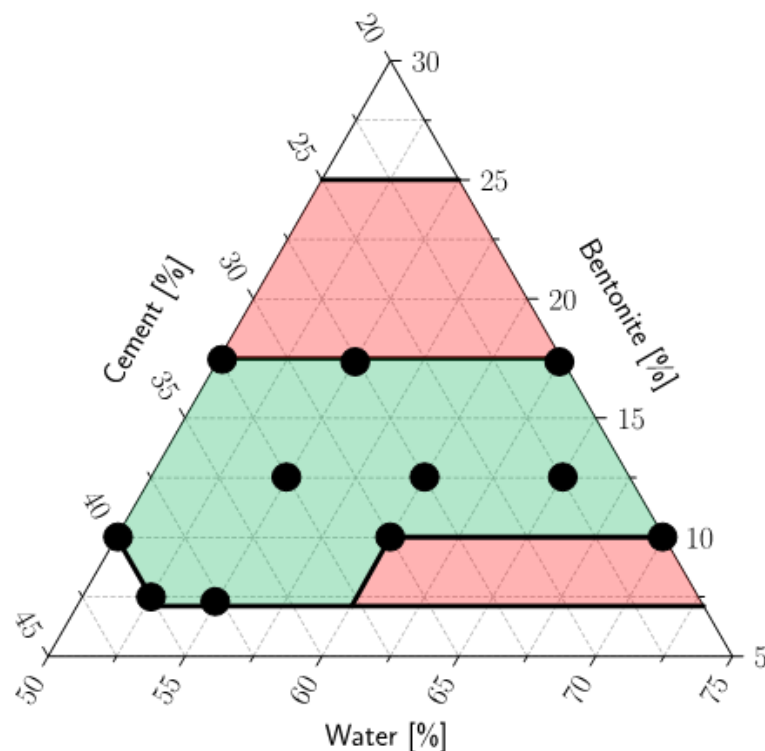


Fig. 4.1: Representation on the ternary diagram of mixtures used in the second stage of the laboratory study

4.2 Sample manufacturing and testing methods

The specimens were fabricated and tested in a manner similar to those made for the first part of the laboratory study. In Fig. 4.2 specimens belonging to the same grouping but with different standardized sand-to-solid ratios are presented. A transition of 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, a yielding mechanism similar to that of soils (with a failure plane at a 45° angle) is observed from specimens with a sand-to-solid ratio of 0.5:1 to specimens with a ratio of 3:1. For the specimen with a ratio of 4:1, failure by compression, typical of weak concretes, was observed.

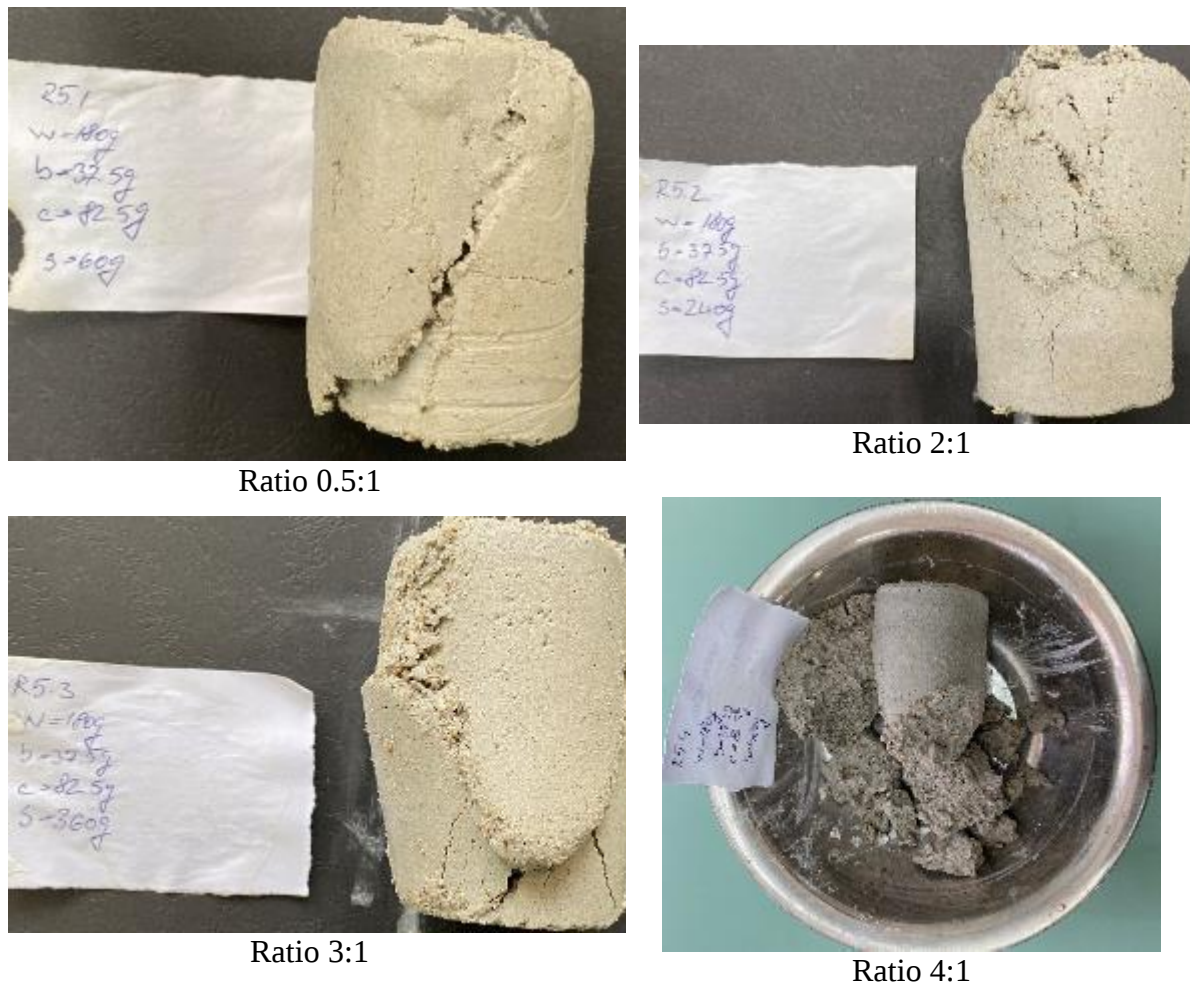


Fig. 4.2: Group of samples after testing

4.3 Laboratory testing results

In Fig. 4.3÷Fig. 4.5 the variations of the parameters determined in the testing program (permeability coefficient, compressive strength, and viscosity) for each sand-to-solid ratio used, namely 0.5:1, 2:1, 3:1, and 4:1, are presented. Particularly, in the representations from Fig. 4.3b÷Fig. 4.3d the influence of a higher amount of bentonite on the mixture is highlighted, showing better hydraulic behaviour of the material, regardless of the amount of standardized sand used. As for the results obtained for the specimens with a sand-to-solid ratio of 0.5:1 (Fig. 4.3a), these can be considered inconclusive. The small amount of sand used in the fabrication of these specimens is the cause of shrinkage phenomena, which in turn resulted in cracks in the specimens' bodies, 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 to the mixture and the fact that a higher amount 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.

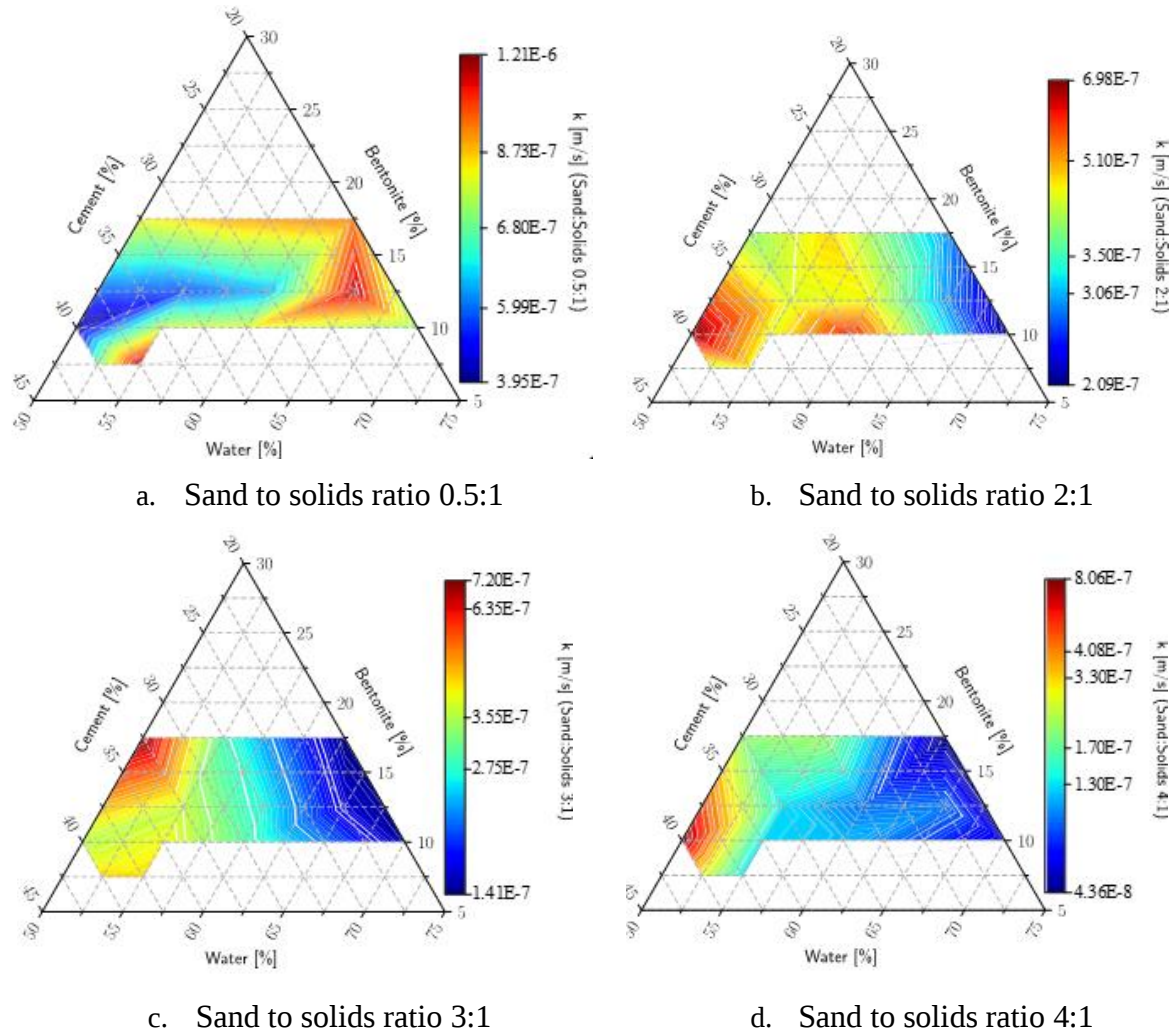


Fig. 4.3: Variation of the permeability coefficient function of the sand to solids ratio

In Fig. 4.4 the variation of compressive strength over the study domain is presented. As determined in the previous study, compressive strength is a characteristic dominated by the amount of cement used in the mixture, with specimens governed by it achieving maximum parameter values. Using a larger amount of cement generates higher compressive strengths.

Additionally, it is noteworthy that the sand-to-solid ratio does not interfere with the value or distribution of compressive strength. The similarity of the results is highlighted in graphs Fig. 4.4a÷Fig. 4.4d. Thus, regarding the influence of the amount of standardized sand on compressive strength, it can be stated that there is no lower limit to the sand-to-solid ratio. However, in terms of the integrity and stability of the mixture, the ratio of 2:1 between sand and solid part used in the mixture is considered sufficient.

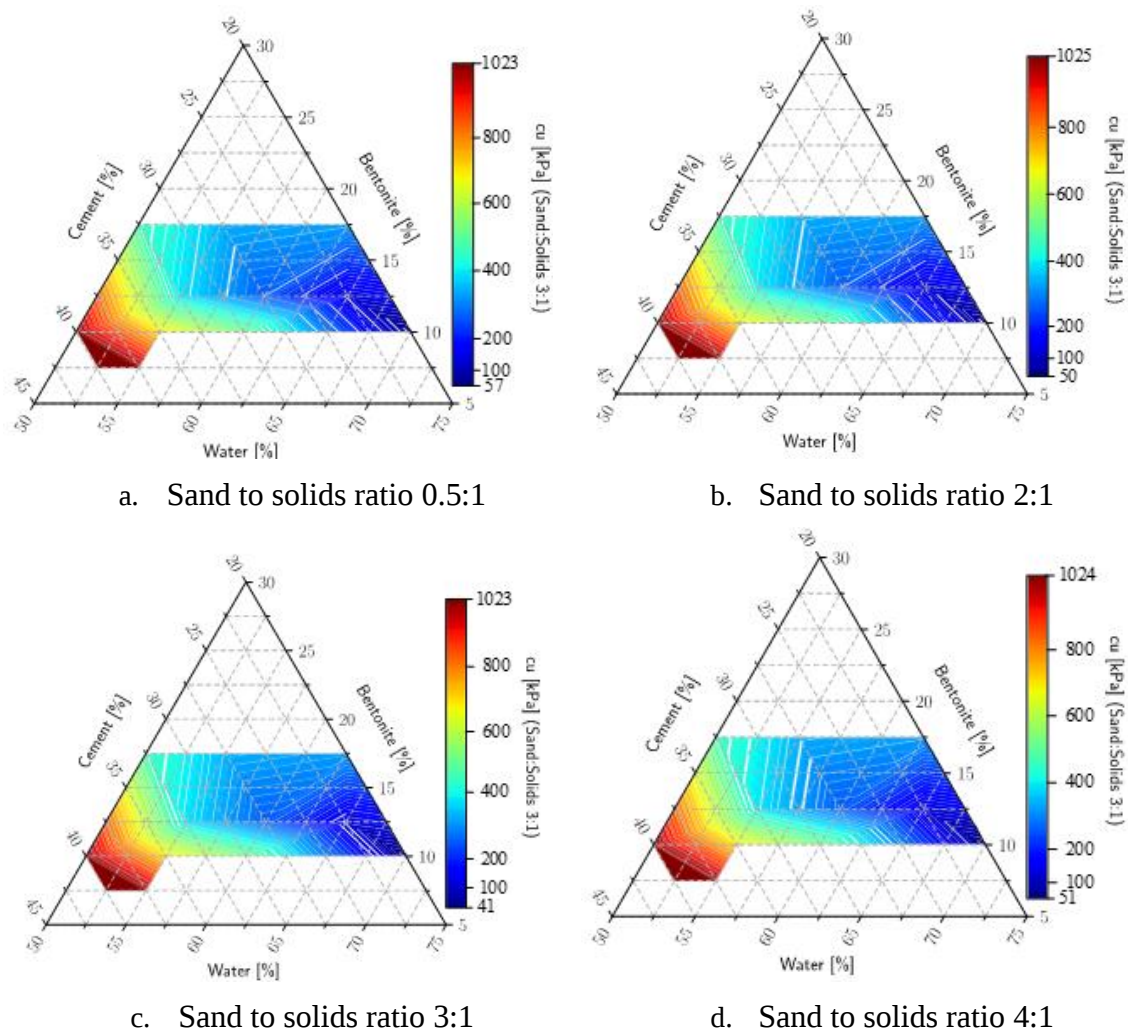


Fig. 4.4: Variation of the compressive strength function of the sand to solids ratio

Fig. 4.5 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. 4.5a÷d that for the same sand-to-solid ratio, a higher amount of water reduces the viscosity, while larger amounts of water and bentonite help create a more viscous paste. In the case of using a larger amount of standardized sand, an increase in extreme viscosity values was also noted: from 31 to 154 Pas for minimum values, and from 448 to 1304 Pas for maximum values. Considering the variation in 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 made during the preparation of the specimens, a sand-to-solid ratio of at least 2:1 provides the material with sufficient workability to be used in practice.

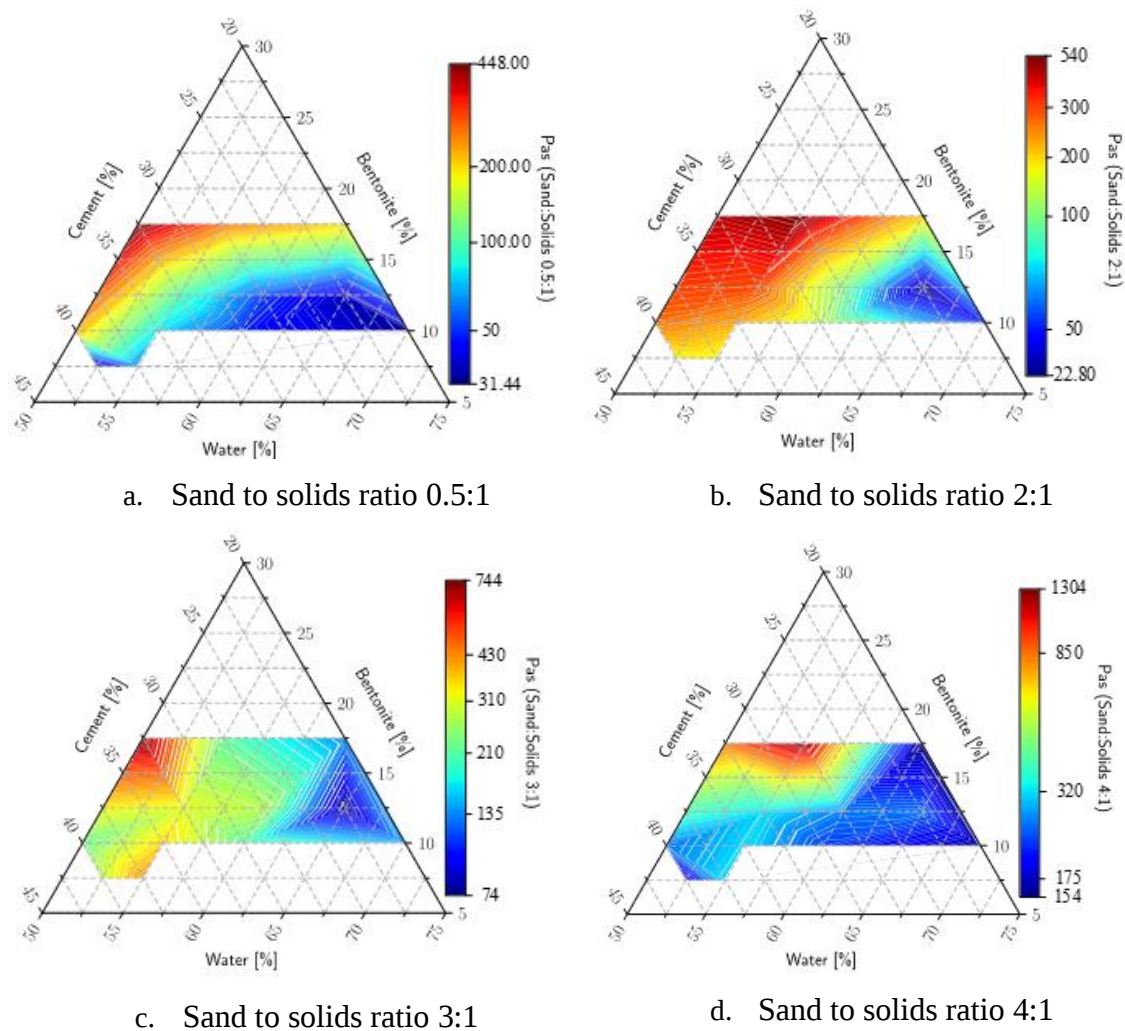


Fig. 4.5: Variation of the viscosity function of the sand to solids ratio

In the case of compressive strength, it can be observed that for specimens governed by the amount of cement, the coefficient of variation has a much lower value compared to specimens dominated by water or bentonite. The fact that specimens with higher water or bentonite content obtained a higher coefficient of variation indicates a greater spread of results under the influence of using a different amount of standardized sand.

Regarding the coefficient of permeability, specimens with higher bentonite content exhibited a lower variation in results regardless of the amount of standardized sand introduced into the mixture, while specimens with a higher cement content exhibited the opposite trend. Taking into account also the results presented in Fig. 4.3, the coefficient of variation of permeability is influenced by the values obtained on specimens with a sand-to-solid ratio of 0.5:1. These values have an atypical spread over the study domain due to contraction phenomena that led to cracks in the specimens. This type of phenomenon was not observed in the case of specimens with sand-to-solid ratios of 2:1, 3:1, or 4:1. In the case of the initially used ratio (Fig. 4.3a) unexpected results were obtained, in the sense that reduced values of the coefficient of permeability were obtained for specimens with a higher cement content. It is worth mentioning that specimens with a higher cement content did not crack.

5 ESTABLISHING THE PARAMETERS FOR MIXTURES WITH OPTIMAL STANDARDIZED SAND-SOLIDS RATIO

5.1 Objectives of the laboratory study

Considering the restricted study area determined in the first part of the laboratory study and the sand-to-solid ratio of 2:1 determined in the second part of the study, in the final stage, four similar samples were manufactured and tested for each type of mixture. The objectives of this final stage are as follows:

- determination of the monitored parameters from the beginning of the laboratory study;
- establishing the degree of confidence in the results obtained both in this final stage and in the previous stages;
- determining the optimal proportions of materials to ensure satisfactory mechanical and hydraulic behaviours.

5.2 Manufacturing of the samples and testing methods

In order to accurately evaluate and compare the characteristics of the mixtures from all research stages, both for sample preparation and for determining physico-mechanical parameters, the same base materials were used, and the work procedures were not modified. Thus, for each of the eleven mixtures, 5 results were used for statistical processing of the parameters.

Due to the already established balance between the proportions of the component materials, after removing the cast the samples, no defects such as cracks or segregations were observed. Additionally, no samples exhibiting a friable behaviour, which could be caused by the homogeneity of the final mixtures, were obtained.

5.3 Test results

The values represented on the graphs showing the variation of physico-mechanical parameters over the study domain (Fig. 5.1, Fig. 5.2) were obtained by averaging the results from laboratory tests. The coefficient of variation was calculated for each set of 4 samples, defined as the ratio of the standard deviation to the mean of the obtained values.

The results regarding compressive strength are presented in Fig. 5.1 highlighting the influence of using a larger amount of cement in the mixtures, with the maximum values of compressive strength obtained in samples dominated by this component. The average values of the parameter vary from 138 to 1164 kPa, also emphasizing the significant difference between using a cement part from 20 to 40% in the mix. These results confirm both the predictions made the beginning of the work and the results obtained in the previous two laboratory studies.

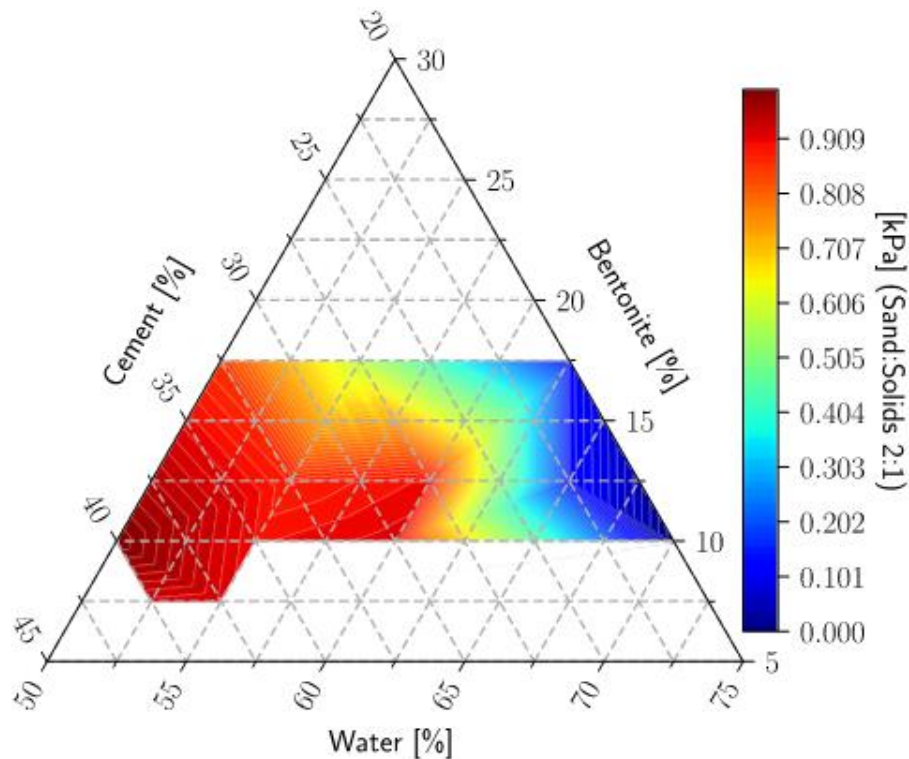


Fig. 5.1: Variation of compressive strength on the study domain

The average values of the coefficient of permeability vary between $7.46\text{E-}07$ to $8.06\text{E-}08$. Higher values of the coefficient of permeability were obtained for samples with higher amounts of bentonite or water, while samples with higher cement content exhibited better hydraulic behaviour. These results can be attributed to physical phenomena during the preparation of the samples, such as: cracking of the specimens due to excessive water content or, conversely, insufficient water content to ensure proper hydration of the bentonite.

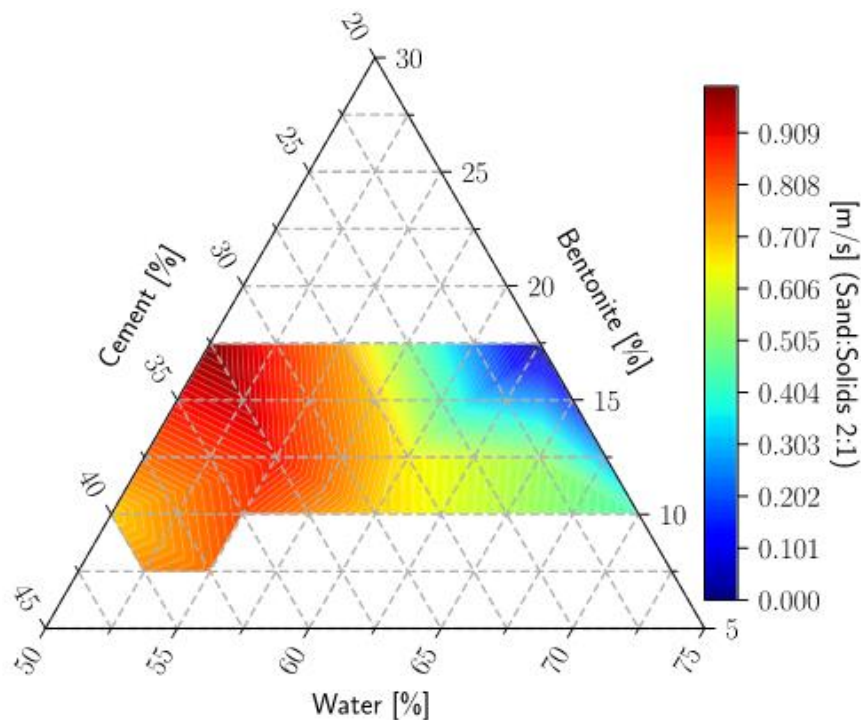


Fig. 5.2: Distribuția coeficientului de permeabilitate pe domeniul de studiu restrâns

5.4 Discussion on the results

In order to highlight the distribution of results and their confidence level, each parameter determined in the laboratory studies was plotted against a representative mass ratio of the water-cement-bentonite mixtures. The ratios used are: water-cement, bentonite-cement, and water-bentonite.

The colours of the markers used on the graphs remained constant for all representations in this subsection in an attempt to simplify visualization and tracking of the final results. For this purpose, the following colour scheme was used:

- Green for results obtained from the third laboratory study;
- Blue for samples from the second study that correspond to those from the last one;
- Red for samples from the second study that do not correspond to those from the last one.

Furthermore, considering the sufficient number of samples made in the third part of the study, for these samples (marked in green), the ranges of variation of the parameters were also represented.

5.4.1 Compressive strength

In the graphs presented in Fig. 5.3, Fig. 5.4 and Fig. 5.5 it is observed that for certain mixtures, especially those with high compressive strength, the results between the second and third parts of the study become similar. This indicates that samples whose behaviour is governed by the amount of cement have a more stable character, and the dispersion of results is reduced.

On the other hand, samples with higher bentonite content show a greater dispersion, which may indicate the negative influence of bentonite on the process of achieving the material class and the induction of effects that cannot be controlled or quantified. The latter aspect is supported by the large differences in compressive strength obtained on similar mixtures, illustrated by the red and green markers. Compared to some samples from the second part of the study, values up to 5 times higher were obtained.

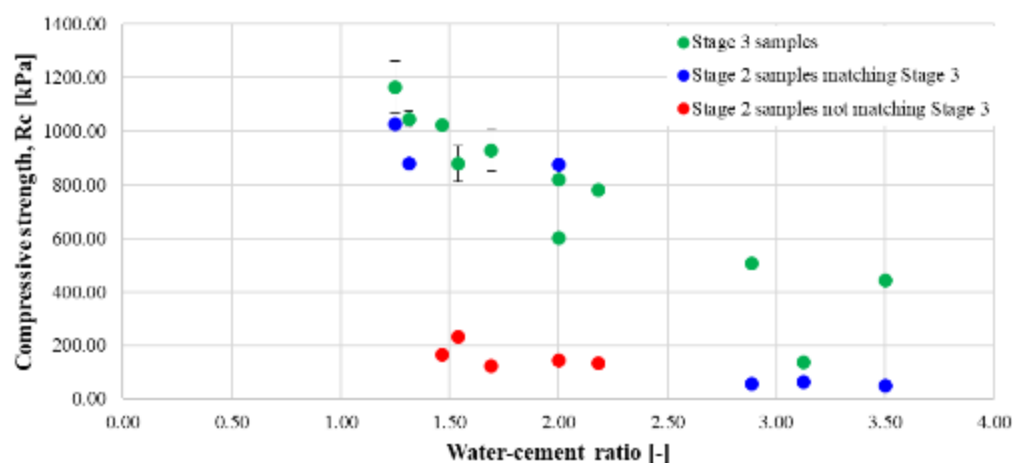


Fig. 5.3: Compressive strength plotted against water-cement ratio

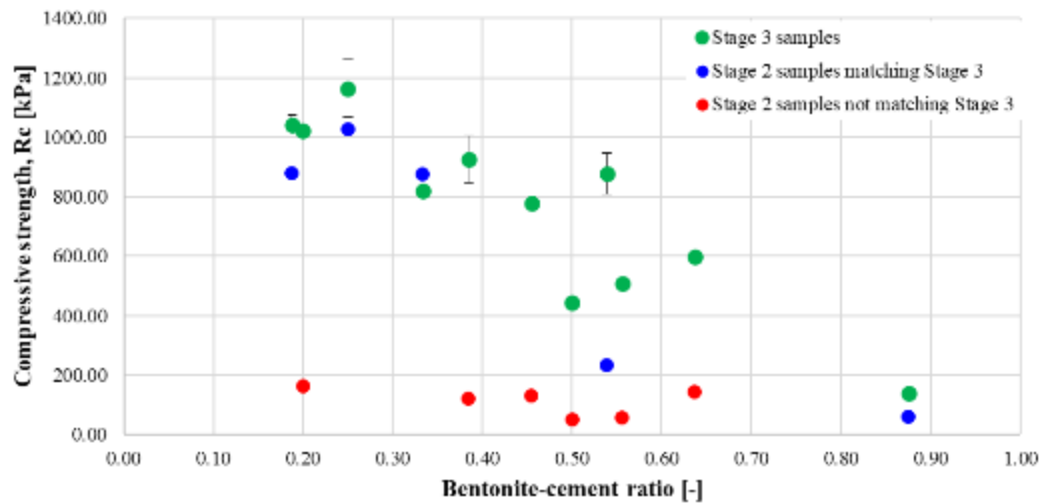


Fig. 5.4: Compressive strength plotted against bentonite-cement ratio

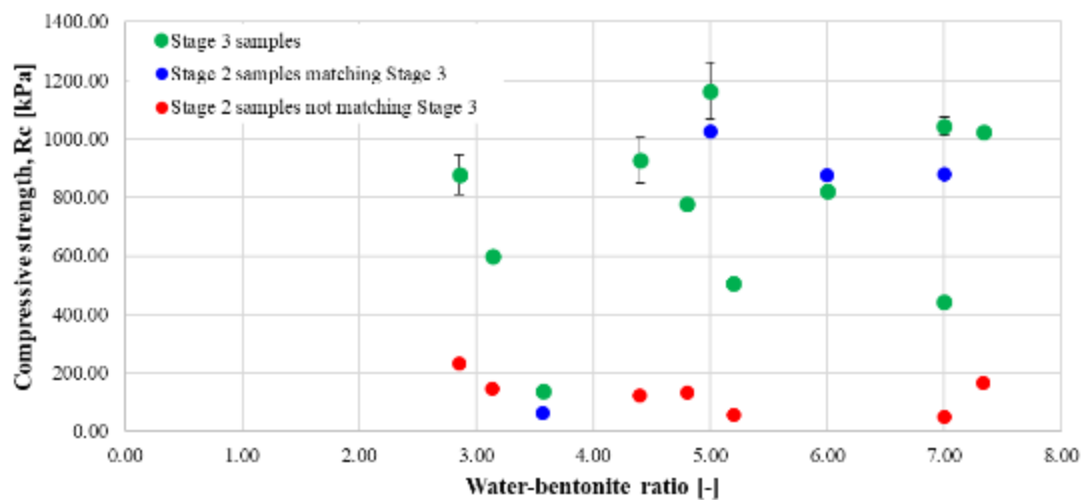


Fig. 5.5: Compressive strength plotted against water-bentonite ratio

5.4.2 Permeability coefficient

According to the graphs presented in Fig. 5.6, Fig. 5.7 and Fig. 5.8, the values of the permeability coefficient fall within the same order of magnitude, 10^{-7} m/s, regardless of the mass percentages used in making the samples. The results obtained in the laboratory studies confirm that the method of preparing and testing the samples was correct, despite the fact that certain results differed for similar samples with the same water-cement and bentonite-cement ratio. In almost all cases presented in the graphs, the values from the second part of the study fall within the range of variation of the samples from the last part of the study.

Furthermore, the representations show that using a larger amount of water leads to higher permeability of the resulting material, while for more stable samples with a higher amount of cement, a higher degree of impermeability was obtained. Despite these differences, the values fall within the same order of magnitude.

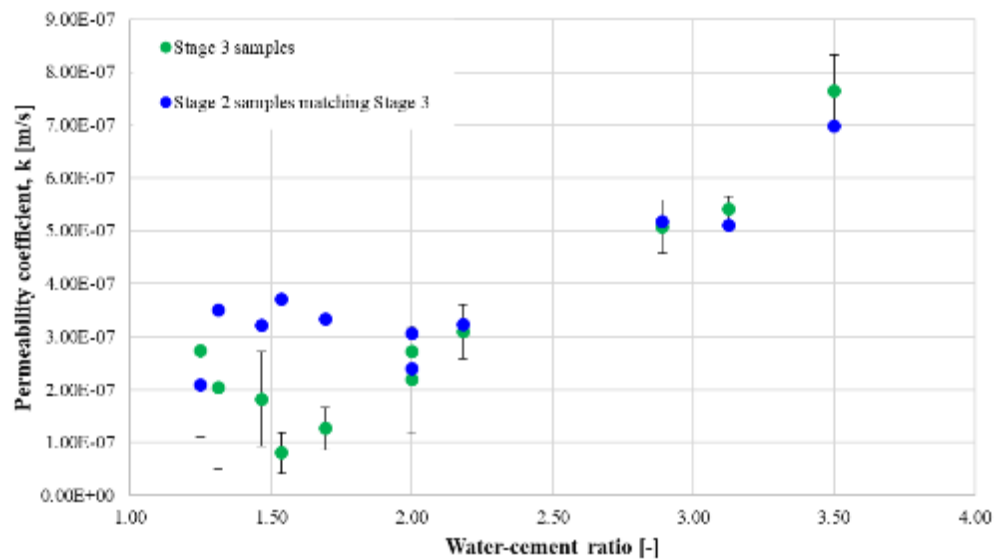


Fig. 5.6: Permeability coefficient plotted against water-cement ratio

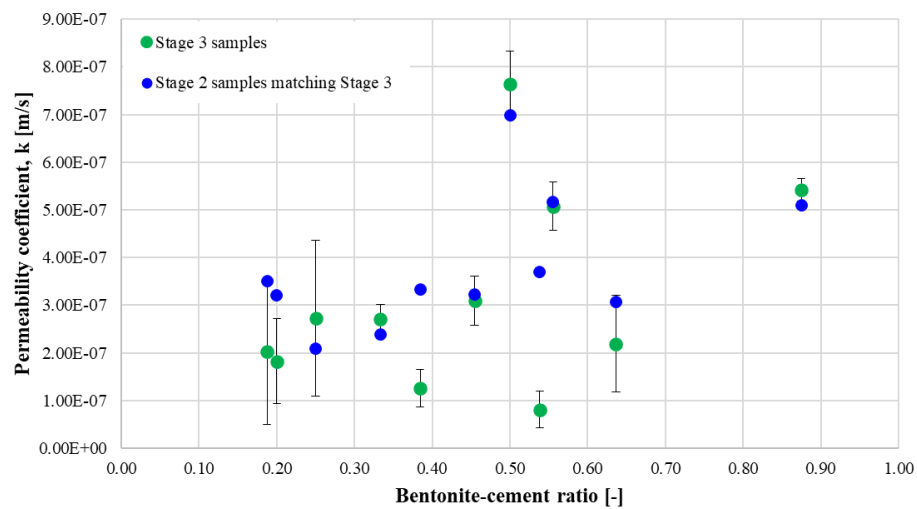


Fig. 5.7: Permeability coefficient plotted against bentonite-cement ratio

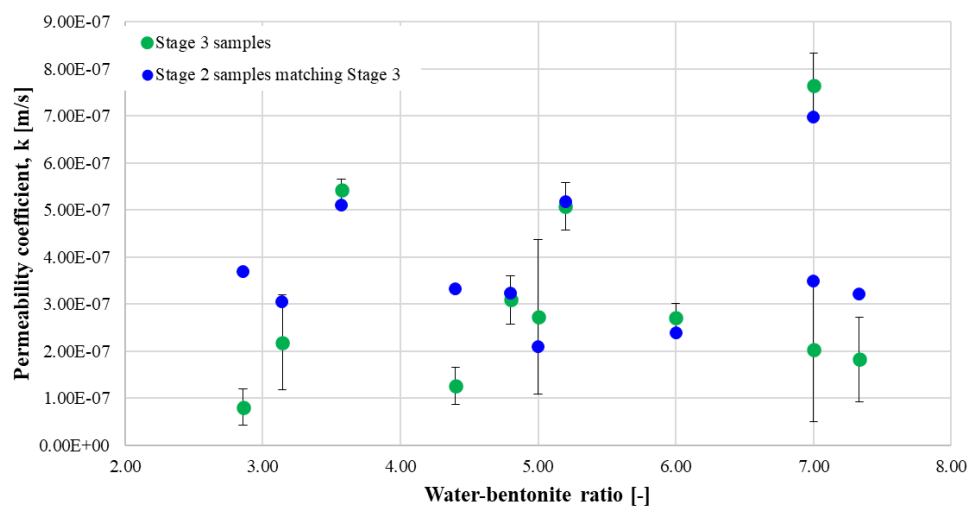


Fig. 5.8: Permeability coefficient plotted against water-bentonite ratio

5.4.3 Viscosity

The viscosity of the material in its fresh state was determined to establish the workability of the material immediately after mixing and to assess its suitability for use. The results of the laboratory studies compared to the characteristic component ratios are presented in Fig. 5.9, Fig. 5.10 and Fig. 5.11.

Regarding this parameter, for a large part of the mixtures, the results were consistent from one study to another. However, there were also several types of mixtures for which the results from the second part of the study did not fall within the variation range determined in the last part. This finding can be attributed to both errors in the preparation or testing of the samples and the thixotropic nature of the material, which is stimulated by its mixing just before the test. Additionally, these results that do not correspond to the variation range highlight the necessity of understanding the material and testing it repeatedly before its use in practice.

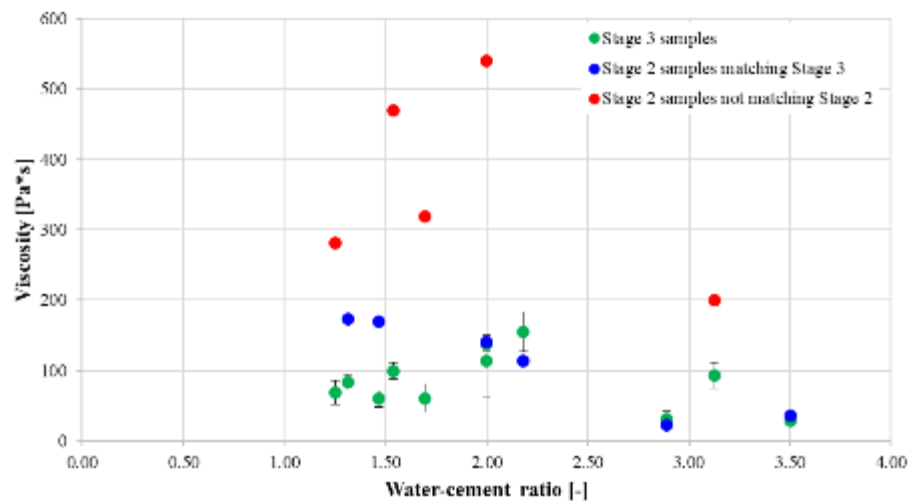


Fig. 5.9: Viscosity plotted against water-cement ratio

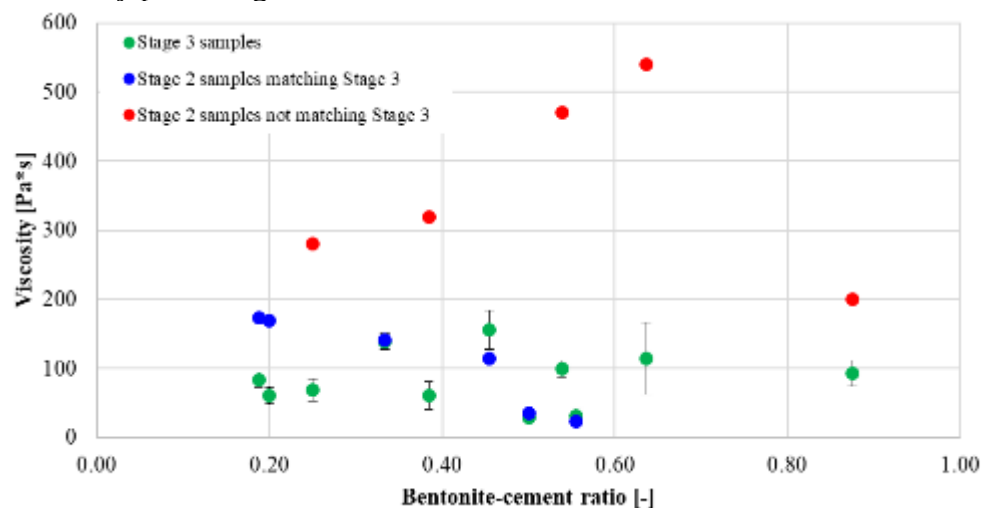


Fig. 5.10: Viscosity plotted against bentonite-cement ratio

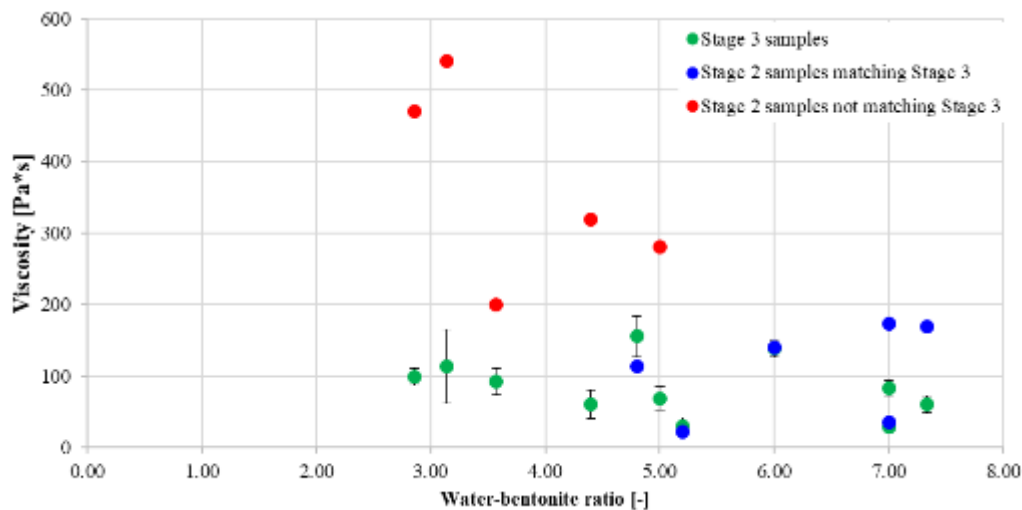


Fig. 5.11: Viscosity plotted against water-bentonite ratio

6 CONCLUSIONS AND ORIGINAL CONTRIBUTIONS

The PhD thesis addresses the topic of sealing material mixtures, presenting and documenting aspects related to their composition, behaviour, and execution technology from the early stages of knowledge and application.

The research presented in this work is based on a thorough study of specialized technical and scientific literature, which has revealed the current state of knowledge. Information related to the materials used (both their nature and methods of use), laboratory preparation and testing methods of the mixtures obtained, as well as the execution technologies of these types of structures, were extracted from the documentary research.

Regarding personal contributions, in the three phases of the study, 140 specimens of water-bentonite-cement mixtures were fabricated and tested. For the study of their properties, in addition to the well-defined methods for determining compressive strength and permeability coefficient in testing standards, laboratory equipment providing repeatable results (viscometer) was used to study the viscosity of the material in its fresh state.

Based on the ternary nature of the mixtures, the barycentric representation was proposed to represent the three basic components (water, bentonite, cement). This representation was maintained in various forms throughout the work and was used to represent the analysed properties. Where necessary, in cases of wide variation domains, logarithmic representation of parameters was also used. The statistical distribution of parameters and the confidence level of the results were highlighted using the same representation.

In the paper, based on laboratory tests, the variation domains of the mass percentages for each main component of the water-bentonite-cement mixture were narrowed down. From the first stage, an approximate limit of 17.5% for the amount of bentonite used was defined to provide the mixture with sufficient hydraulic and mechanical behaviour.

Throughout the research, it was demonstrated that samples with a higher content of bentonite do not necessarily ensure better hydraulic behaviour. This fact was attributed to the interference between the hydration processes of bentonite and cement. Calcium bentonite, requiring more water to hydrate, can affect the hydration of cement, thus reducing compressive strength and prolonging setting time. Especially in the first part of the laboratory research, when a wider

range of variation was used for the composition of mixtures, segregation, cracking, or contraction phenomena were observed. These aspects highlighted the effects of insufficient or excessive amounts of water and the interference between the hydration phenomena of cement and bentonite.

Additionally, as a result of compressive strength tests, two types of yield mechanisms were observed, attributed according to the dominant component in the mixture. For samples governed by the amount of bentonite, a mechanism similar to that of soils was noticed, characterized by a yield plane inclined at approximately 45° , while for samples with a higher cement content, a yield similar to that of weak concretes (brittle yield by compression) was observed.

Another conclusion obtained from the tests was the establishment of the standardized sand-to-solid ratio at a value of 2:1. This value was considered sufficient not to influence the physico-mechanical parameters of the material and not to affect the structural integrity of the specimens through contraindicated phenomena such as segregation or cracking. In the three stages of research, the variation domain of the components was strongly limited, making it possible to define barycentric diagrams to assist in the design of mixtures according to the desired characteristics.

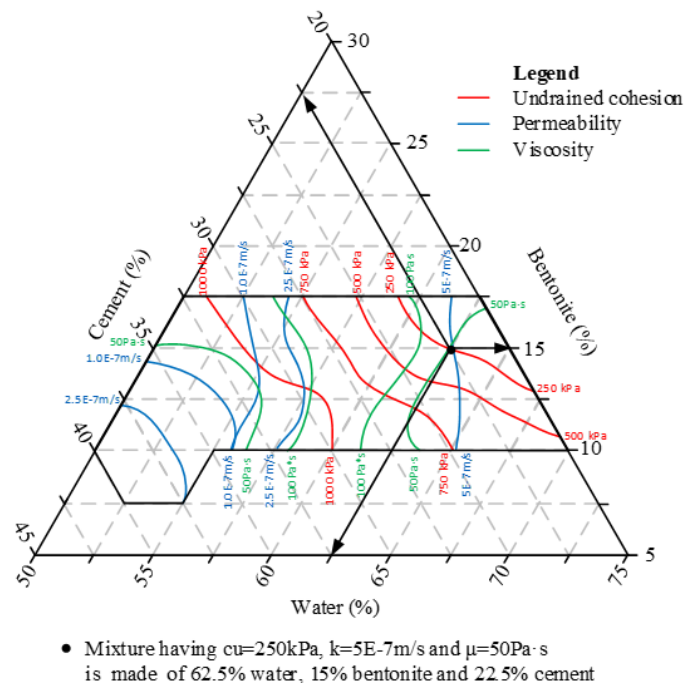


Fig. 6.1: Barycentric computation model

It is important to use mixtures judiciously, considering that the addition of bentonite does not always improve the desired physico-mechanical properties. The way materials are used, as well as the mixing and composition procedures, have physical limits beyond which significant improvements are unlikely.

This thesis focused exclusively on unaltered mixtures, but an important research direction would be the contribution of additives (plasticizers, accelerators or retarders, etc.) to the material properties. Although not necessarily recommended, the behaviour of mixtures with other types of cement and bentonite should be studied, especially for temporary structures where rapid behaviour is desired without the need for a long-life span for secondary chemical reactions to occur (isomorphic substitutions, electrophoresis, etc.). This study should focus particularly on rheological research.

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