Use of Municipal Waste to Build Ecological Blocks

Eduarda da Conceição Nepomuceno

Dissertation presented to the School of Technology and Management of Bragança to obtain the Master Degree in Construction Engineering.

Work oriented by:

Débora Rodrigues de Sousa Macanjo Ferreira

Eduarda Cristina Pires Luso

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Abstract

The reduction of natural resources leads to the search for new alternatives, and the construction sector, as the largest consumer of these resources, if the conventional raw materials were substitute with recycled material it will causes a greatest positive impact. This work evaluates the mechanical and durability characteristics and resistance to high temperatures of soil-cement cylindrical specimens in three different compositions. A comparison between specimens with residues and specimens without residues (reference) is proposed, to investigate the possibility of being used as non-load bearing masonry walls. The characterization tests are based on Brazilian standards and compared to Spanish and German standards. For the high temperature analyses European standards and the ISO heating curve are used. After laboratory tests and comparative analysis between the specimens, was verified a drop in the performance of the specimens with residues, but the alternative of being used can not be discarded, since all are within the limits established by the standards used.

Keywords: Soil-cement; Ecological blocks; Organic waste; Sustainability

Resumo

O escassez dos recursos naturais leva à procura de soluções alternativas, e o setor de construção, como maior consumidor desses recursos, é o que causa maior impacto positivo se substituir essas matérias-primas convencionais por materiais reciclados. Com o propósito de aumentar o uso de resíduos nos materiais de construção, esse trabalho avalia as características mecânicas, de durabilidade e de resistência a altas temperaturas de amostras cilíndricas de solo-cimento em três composições distintas. Uma comparação entre amostras com resíduo e amostras sem resíduos (referência) é proposta, para averiguar a possibilidade de serem utilizados como elementos de paredes não estruturais. Os ensaios de caracterização são baseados em normas brasileiras e comparados com normas espanhola e alemã. Para as análises à altas temperaturas normas europeias e a curva ISO de aquecimento são utilizadas. Após ensaios laboratoriais e análises comparativa entre os blocos, verificou-se queda no desempenho dos corpos de prova com resíduos, porém a alternativa de serem utilizados não pode ser descartada, pois todos estão dentro dos padrões estabelecidos pelas normas utilizadas.

Palavras-chave: Solo-cimento; Bloco ecológico; Resíduo orgânico; Sustentabilidade

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Acronyms

AASHTO American Association of State Highway and Transportation Officials.

ABCP Brazilian Portland Cement Association.

ABNT Brazilian Association of Technical Standards.

AK Class of Block.

ANN Artificial Neural Network.

ASTM American Society for Testing and Materials.

BC Before Christ.

CDW Construction and Demolition Waste.

CEB Compressed Earth Blocks.

DAQ Data Acquisition.

DIN German Standard.

E Integrity.

EN European Standard.

ESTiG School of Technology and Management.

I Insulation.

IPB Polytechnic Institute of Bragança.

ISO International Standard.

M Mechanical Action.

PI Plasticity Index.

PID Proportional Integral Derivative.

RHA Rice Husk Ash.

SC Clayey Sand.

SF Silica Fume.

UNE Spanish Standard.

W Radiation.

WWTP Wastewater Treatment Plant.

Symbols

γ Bulk Density.

γ_d Dry Unit Weight.

γ^d_{max} Maximum Dry Unit Weight.

λ Thermal Conductivity.

ω_{opt} Optimum Water Content.

c Specific Heat.

Chapter 1

Introduction

This work statements the current issue of sustainability combined with development in construction. The purpose is to expand the use of ecological blocks and lessen the environmental impact that the construction industry has causing for years. To begin the work, will be carried out preliminary studies and experiments test that will allow select the best methods. After the preliminary stage, cylindrical specimens will be constructed, which will undergo tests and comparative analyses with the reference standard.

1.1 Motivation and Framework

The construction sector is one of the largest consumers of natural resources. These resources are scarce and finite, and it is necessary to search for other sources. In this context, the use of recycled and recyclable materials has great potential for applicability in civil construction. In addition to the raw materials, the energy incorporated in the construction processes is extremely high, from the manufacturing to its transport.

Each year millions of tons of urban waste are generated in Brazil and Portugal. In 2016 the per capita generation of municipal waste was 1.040 kg/inhabitant/day in Brazil [1] and 1.299 kg/inhabitant/day in Portugal [2]. This large amount of waste, if not properly collected and deposited, can lead to health problems. But even in cases of correct destination, these wastes are overcrowding landfills. So using these was more ecological purpose, and not just discarding it, can generate a number of benefits.

Some of the materials most used by traditional construction require high temperatures for their production, causing release of polluting gases into the atmosphere, such as ceramic bricks and Portland cement. In addition, these materials have high energy value incorporate in their manufacturing and transportation process. The use of soil as building material improves both problems. The construction of Compressed Earth Blocks (CEB) does not require burning, eliminating the gases that are released in the air, furthermore, the earth can be easily found in practically all the parts of the planet, which reduces the costs of transport.

In this work was studied the use of solid urban waste incorporated in soil-cement cylindrical specimens. With the purpose of will be use in non-load bearing masonry walls.

1.2 Objectives

The main goal of this work is to propose technical and constructive solutions for the manufacture of soil-cement cylindrical specimens with the addition of organic urban waste that can later be used in non-load bearing masonry walls. Therefore the others objectives also make up this work:

- Propose solutions that allow the ideal reaction between the organic compound and the soil-cement.
- Perform immersion water absorption test.
- Perform durability testing through wetting and drying cycles.
- Perform compressive strength test in four different conditions: standard, saturated, aged and under high temperature.
- Compare the tests results with the standards used and with each other.

1.3 Document Structure

This document is divided into 6 chapters, to describe the work carried out throughout the dissertation.

Chapter 1 addresses the introduction of the work. Exposing the proposal of the work as well as the motivation and framing of the theme.

The history of earth construction, its advantages and disadvantages, and the current requirements for these constructions are presented in Chapter 2. In this chapter, previous studies on the subject are also presented with several approaches.

Chapter 3 presents the properties of the materials that will make up the soil-cement specimens, being these: soil, cement, water, silica and residue. Through these properties it is possible to determine the suitability of the materials available for the construction of the specimens.

Chapter 4 presents the preliminary studies, as well as the methods used to choose the proportions and manufacture of the specimens. This chapter also presents the procedures and equipment used.

Chapter 5 is dedicated to the results, presenting all the analyses of each test separately and making comparisons between the specimens with residues and the reference specimens and still verify if they accordance with the standards used.

Finally, the conclusions obtained in this dissertation are presented in Chapter 6, suggestions are also presented for the continuation of studies in future works.

Chapter 2

Earth Construction

Earth building is an age-old practice and it is not known for sure when it first appeared, there are estimates based on ancient earth constructions. The oldest earth blocks found are from Mesopotamia, in the upper Tigris basin, and date back to 7500 Before Christ (BC) these data lead to the estimation that earth construction exists at least 10000 years [3].

The availability of earth for the application as building material and the fact that it is environment friendly is a reason to broaden the studies and increase its use. The areas that use earth construction the most are in less industrialized and developing countries, and more than 30% of the world's population live in earth houses [3]. Figure 2.1 shows the locations of the world where there are buildings of earth, listed in 2010, some of which are listed as World Heritage.

There are buildings in earth dating back centuries that have stood the test of time and can still be seen today. The Great Wall of China started 3000 years ago, initially built in rammed earth, and then lined with stone masonry (Figure 2.2a). In Algarve, the Paderne Castle, built in rammed earth, is an example of 12th century earth construction (Figure 2.2b). Another great construction is the pyramid of Uxmal, in Mexico, built between the 6th and 10th centuries (Figure 2.2c). The still-inhabited city of Shibam, Yemen, with walls made of adobe blocks, is more of an old building in earth, its walls decreasing the thickness according to height (Figure 2.2d) [5], [6].

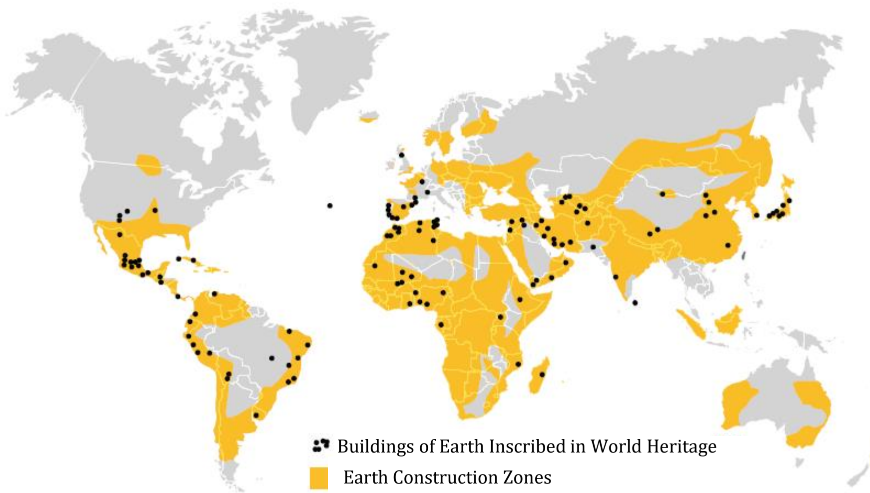


Figure 2.1: Earth Construction in the World (adapted from [4]).

(a) Great Wall of China [7]

(b) Paderne Castle [8]

(c) Pyramid of Uxmal [9]

(d) Building of Shibam [10]

Figure 2.2: Historic Earth Constructions.

2.1 Advantages and Disadvantages

Earth construction is a sounding topic nowadays, with growing interest due to the high sustainability. In fact, earth construction can constitute a feasible solution for a more sustainable construction industry in developed countries. The methods of construction in earth are varied, each of these methods having its own advantages and disadvantages. This section presents the main advantages and disadvantages of earth construction in general.

2.1.1 Advantages

The main advantages highlighted for the use of the earth as construction material are [11], [12]:

- Availability, accessibility and low cost; the soil is a material available in large quantities in almost every part of the world, being a material with reduced cost.

- Easy-to-handle technology; the techniques to build with earth are simple and can be passed down through the generations.

- Good thermal properties; walls built with soil have good thermal behavior, with capacity of absorption and release of humidity that enable the keeping the temperature.

- Low energy expenditure; as the manufacturing process of the walls and bricks does not require burning, the energy expenditure is significantly decreased, being about 1% of the energy required to produce the same volume of cement concrete.

- Environmentally friendly; the soil is used in the natural state, with low energy consumption and minimal pollution (low CO_2 emissions) and capacity to return the earthen materials back to nature after their life-cycle.

- The earth present a good resistance at fire.

2.1.2 Disadvantages

The disadvantages of the construction with earth some characteristics are highlighted, among which [12]:

- Reduced durability; if not regularly maintained and protected of wet areas.
- Low tensile strength; as well as concrete the tensile strength of the construction with earth is not sufficient and is advised only for use in compression.
- Low resistance to abrasion and impact; in addition to tensile strength, these also do not stand on their own, and reinforcements are required where this type of request is predicted.
- However, the major drawback is that traditional earthen materials are typically considered as non-standard. The great variability and heterogeneity of the properties of the available soils, the lack of quality control in the manufacturing of the earthen materials and in the construction process can be pointed out as the main reasons behind this situation.

To finalize this section it is important to highlight that the advantages and disadvantages are according to the methods of construction and soil stabilization. These methods are varied and depend on the region and the desired characteristics for the construction. In the next sections, the most used methods are presented for both the construction and soil stabilization.

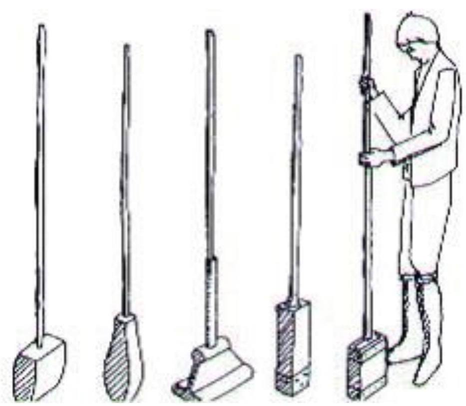
2.2 Earth Construction Methods

There are numerous techniques to build with earth, as it can vary depending on the culture, type of soil available, local climate, economy and other factors. These techniques can be divided into three large groups: masonry, monolithic and mixed. Masonry is characterized by building of structures with individual units, often laid bring together by mortar. The monolithic is moist earth usually compacted on wood formworks. In the mixed, the soil serves as a filler for a structure of wood or bamboo, having no structural function [11], [13]. The following are the most common methods applied.

2.2.1 Rammed Earth

Rammed earth is a monolithic wall compacted, with moist earth and between wooden formwork (Figure 2.3a) that moves as the progression of the construction. The compaction of the earth can be manual or mechanical, by pestles, as shown in Figure 2.3b. Guides and stems are used to ensure that the wall is flat and to facilitate the movement of the molds [14]. It is a material with good thermal inertia, and has low resistance to moisture; therefore it is not advisable for very humid regions [15].

(a) Formwork



(b) Pestles

Figure 2.3: Materials for Rammed Earth [6].

2.2.2 Wattle & Daub

Wattle & Daub is a mixed construction technique, in which bamboo or fibers wood are used to form a structure. The space is filled with earth in both sides simultaneously. This technique causes many cracks in the walls, requiring coating [14], [15]. This structures are suitable for seismic regions because they present excellent performance in this situations [14]. Figure 2.4 shows a wall constructed by this technique.

Figure 2.4: Walls of Wattle and Daub [6].

2.2.3 Adobe

The adobe is framed in masonry technique and consists of earth bricks mixed with water. In this method there is no compaction, being the oldest technique of masonry in earth, its characteristics were improved initially adding natural asphalt and straws, wooden formworks are used for their confection (Figure 2.5a) and later they are dried in the sun, presented in Figure 2.5b [14], [16]. The execution is similar to conventional masonry, that is, the bricks are joined by means of mortars, with the difference that in this type of brick can be used for the mortar the same material that makes up the brick [14].

(a) Formwork

(b) Adobe Dried in the Sun

Figure 2.5: Adobe Manufacturing [14].

2.2.4 Compressed Earth Block

The CEB among the techniques of construction in earth is the most used today. Figure 2.6 shows a construction using this technique of masonry. They are blocks with high resistance, exceeding sometimes the traditional ceramic bricks. Different from adobe these blocks are always compressed, and the compaction can be either manually or by hydraulic presses, in various shapes and sizes. They can be docking structures, or as well as adobe bring together by mortar. CEB are always stabilized, usually with lime or cement [15].

Figure 2.6: Construction of walls with CEB [17].

2.3 Soil Stabilization

Soil stabilization seeks to improve granulometric, strength and durability characteristics, and also to modify the Plasticity Index (PI) of the soil to be used, the most common stabilizing additives are bituminous and chemical, such as cement, lime and fly ash [18], [19].

Chemical stabilizations can be combined, as lime-cement and lime-asphalt. The combinations are used according to the changes wanted from the available soil. For example, lime improves workability, modifies soil gradation and can reduce the PI if used as a preliminary additive, and may after those improve water and mechanical resistance with cement addition [13], [19].

In order to choose which stabilization method for the soil, some studies are available. Figures 2.7 and 2.8 are based for the choice of stabilizing agent, the plasticity index and granulometry, where it is possible to choose between bitumen, lime or cement.

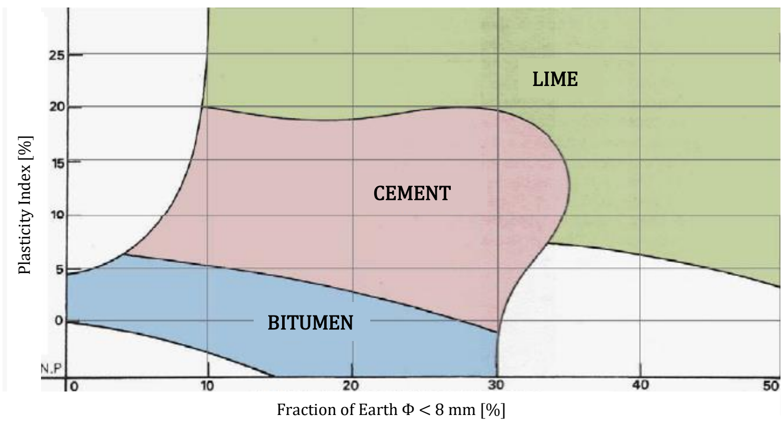


Figure 2.7: Graph for Stabilizer Agent Choice (adapted from [20]).

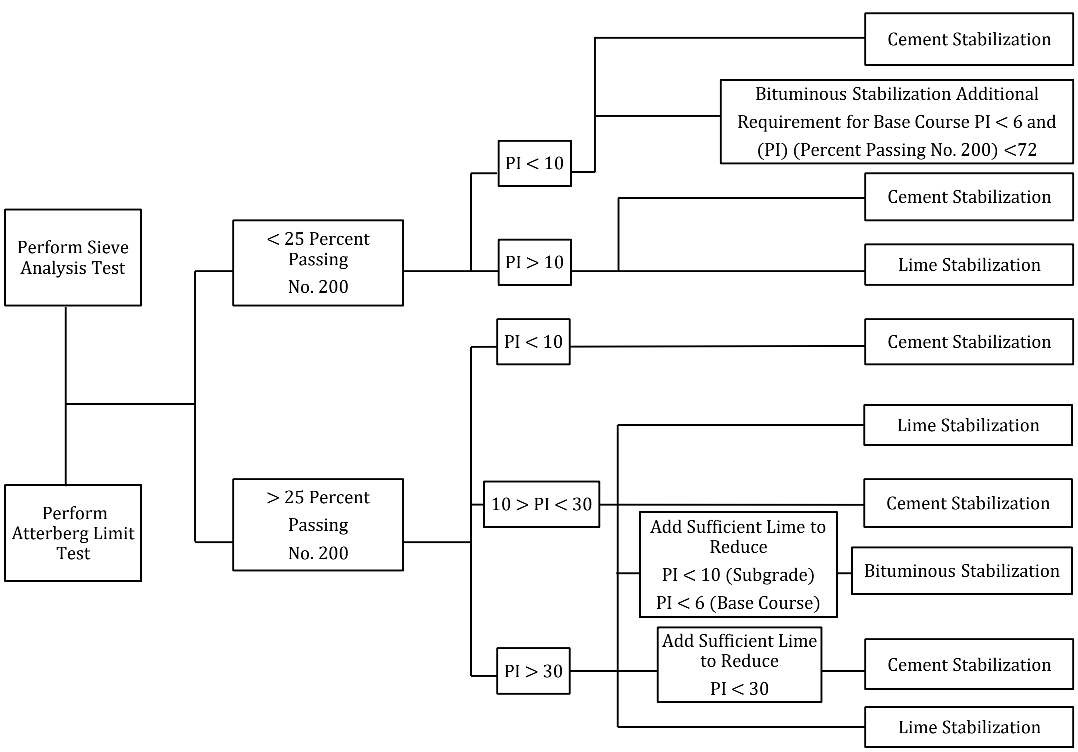


Figure 2.8: Flowchart for Stabilizer Agent Choice [21].

After analyzing the Figures 2.7 and 2.8, it is noticed that the soil stabilization with cement is the combination with greater possibility for a greater types of soils, for this reason is the most used. This stabilization is known as soil-cement.

2.4 Soil-Cement Characterization

Soil-cement is a homogeneous compacted mixture of soil, Portland cement and water in rational dosage, which has a good waterproofing index, low shrinkage, good compressive strength and durability when properly cured, in the shape of bricks, blocks or monolithic walls [22]–[25].

The soil-cement is further described as a mixture stabilized by physicochemical process, resulting from the reorientation of the structuring of soil with cement particles that has intergranular contacts, modifying the relative amounts of solids, liquids and gases of the composition [16].

2.5 Soil-Cement Blocks Requirements

Soil-cement blocks must have some minimum conditions required to be used. These requirements are specified by standards worldwide, as in Brazil, Colombia, Spain, France, Italy, among others [26]. As this work involves two countries, Brazil and Portugal, the standards in which the conditions were satisfied, should be evaluated. However in Portugal there is no standard for CEB, standards from other countries for comparison with Brazilian standards were analyzed, namely Spain and Germany Standards.

2.5.1 Brazilian Standards

In Brazil the standards for soil-cement blocks are made by Brazilian Association of Technical Standards (ABNT) and Brazilian Portland Cement Association (ABCP).

The first requirement to be met for the production of CEB is in relation to the soil. Table 2.1 presents the characteristics of the soil must meet, like granulometry, the liquid limit and the plasticity index.

Table 2.1: ABNT Recommendations for Soil (adapted from [27]).

Requirement	Value	Unit
Passed in the ABNT 4.8 mm	100	%
Passed in the ABNT 0.075 mm	10 to 50	%
Liquid limit	≤ 45	%
Plasticity index	≤ 18	%

The cement that will be part of the CEB must be standardized, and the types of cements suitable for the production of CEB are specified, see Table 2.2. In addition to the type of cement, is specified the minimum and maximum content of cement that can be used. These values are 5% and 10%, respectively [22], [28].

Table 2.2: ABNT Recommendations for Cement (adapted from [29]).

Cement Type	Description
CP I	Ordinary
CP V-ARI	High Early Strength
CP III	Portland-Slag Cement
CP IV	Portland-Pozzolan Cement

For compressive strength, CEB must meet individual and average minimum values, with minimum curing ages of 7 days, as well as maximum values, individual and medium, of water absorption. These values are presented in Table 2.3. If these values are not meet, the blocks must be rejected [29].

Table 2.3: ABNT Mechanical and Absorption Requirements (adapted from [29]).

Test	Individual Value	Average Value	Unit
Compressive Strength	≥ 1.7	≥ 2.0	MPa
Water Absorption	≤ 22	≤ 20	%

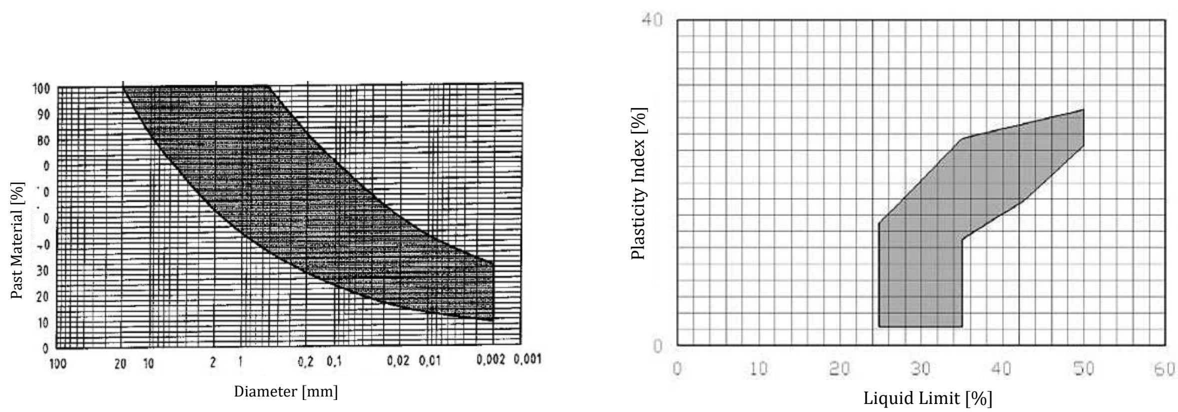
The concept of durability of CEB in Brazil is evaluated by wetting and drying cycles, where the mass losses, moisture variation and volume variation of the analyzed material are verified [30]. The maximum mass loss values that the blocks can suffer after the cycles are shown in Table 2.4, these values are specified according to the American Association of State Highway and Transportation Officials (AASHTO) classification of soils.

Table 2.4: Limits of Mass Loss ABCP (adapted from [22]).

AASHTO Classification	Loss of Permissible Mass	Unit
A1, A2-4, A2-5 and A3	14	%
A2-6, A2-7, A4 and A5	10	%
A6 and A7	7	%

2.5.2 Spanish Standard

In the case of Spanish Standard (UNE), the soil classification is given at intervals, for granulometry and for the plasticity index and liquid limit. Figure 2.9 shows these intervals. Soils with clay content less than 10% are not allowed [31].



(a) Interval of the Grain Size Curve (b) Recommended Plasticity Zone

Figure 2.9: UNE Recommendations for Soil (adapted from [31]).

The type of cement that can be used in the soil-cement mixture is not specified, but it must be cement that complies with a serial of standards, including the European Standard (EN) 197-1 [32]. Some manufacturers, which produce cements according to the cited standard, recommend for soil stabilization the cements shown in Table 2.5. The maximum content of cement should be 15% in relation to the dry mass of soil [31].

As for the compressive strength, a table is given in which it presents the average values of normalized resistance with standard deviation of 5%, and classifies the CEB in blocks of 1 to 3 according to these values. It is also stated that no result should be less than 80% of the mean value specified in Table 2.6.

Table 2.5: Manufacturers Recommendations for Cement (adapted from[33]).

Cement Type	Description
CEM II/ A-L 42.5 R	Portland-Limestone Cement
CEM II/ B-L 32.5 N	Portland-Limestone Cement
CEM IV/ B (V) 32.5 N	Portland-Pozzolan Cement

Table 2.6: Compression Strength Class of CEB (adapted from [31]).

Blocks	Value	Unit
CEB 1	1.3	MPa
CEB 2	3.0	MPa
CEB 3	5.0	MPa

To analyze the durability of CEB, wetting and drying cycles, freezing and thawing cycles and erosion resistance are examined. Tables 2.7 and 2.8 shows the criteria for accept or not the blocks.

Table 2.7: Criteria for Rejection in Wetting and Drying Cycles (adapted from [31]).

Analysis	Criteria	Result
Cracking pattern	Random	Not Accept
Cracking pattern	In star	Not Accept
Swelling	Local	Not Accept
Local cut	at least 5 zones	Not Accept
Loss of soil layers	General or local	Not Accept
Penetration of water	$\geq$ 70% width	Not Accept
Loss of fragments	$\geq$ 50 mm	Not Accept
Surface Efflorescence	Visually	Not Accept

Table 2.8: Erosion Resistance Criteria (adapted from [31]).

Aspect	Criteria	Result
Depth of Cavity (D)	$0 \leq D \leq 10$ mm	Accept
	D >10 mm	Not Accept

2.5.3 German Standard

The first specification in the German Standard (DIN) concerns the Class of Block (AK), these are divided by field of application in relation to the humidity that will be exposed, and these classes are presented in Table 2.9.

Table 2.9: Application Class of Bricks (adapted from [34]).

Application Area	AK
Plastered, masonry exposed to weather	Ia
Usually plastered, masonry exposed to weather	Ib
Protected exterior masonry or internal masonry	II
Dry application (e.g. ceiling)	III

The compressive strength, just like in the Spanish Standard, is divided by classes of strength, ranging from 2 to 6, and the minimum and average values of these classes are presented in Table 2.10, the blocks must meet at least class 2.

Table 2.10: Block Compressive Strength Class (adapted from [34]).

Class	Average Value	Minimum Value	Unit
2	2.5	2.0	MPa
3	3.8	3.0	MPa
4	5.0	4.0	MPa
5	6.3	5.0	MPa
6	7.5	6.0	MPa

Also, as in previous standards, there are specifications on the evaluation of the blocks for moisture and freezing, shown in Table 2.11. These evaluations are dependent on the class AK of the block, being the class Ia the most rigorous evaluation.

Table 2.11: Behavior to Moisture and Freezing (Adapted from [34]).

AK	Immersion Test Loss of Mass [%]	Visual Analysis	Capillary Water Absorption [h]	Freezing and Thawing Cycles
Ia	≤ 5	No cracking or swelling	≥ 24	≥ 15
Ib	≤ 5	No cracking or swelling	≥ 3	≥ 5
II	≤ 15	No cracking or swelling	≥ 0.5	No requirements
III	No requirements	No requirements	No requirements	No requirements

2.6 Thermal Characteristics

There are no thermal requirements for the CEB. However, these blocks are expected to meet the same requirements as traditional masonry blocks. For this purpose, thermal comfort and fire resistance standards were evaluated for traditional blocks that could be used as requirements for soil-cement blocks.

The Brazilian Standard presents the thermal properties that each type of material must have. Table 2.12 shows the properties for clay bricks, namely Bulk Density (γ) , Thermal Conductivity (λ) and Specific Heat (c).

Table 2.12: Thermal Properties for Clay Bricks and Tiles (adapted from [35]).

γ [kg/m^3]	λ [W/m · K]	c [kJ/(kg · K)]
1000 to 1300	0.70	0.92
1300 to 1600	0.90	0.92
1600 to 1800	1.00	0.92
1800 to 2000	1.05	0.92

For high temperature analysis, the ISO 834-1 [36], describes the conditions of the thermocouples and the way of monitoring the furnace heating, which must conform to the standard curve, through the equation 2.1.

$$T = 345 \cdot log_{10}(8t + 1) + 20 \tag{2.1}$$

Where T is the average furnace temperature, in degrees Celsius; and t is the time, in minutes.

And according to this relationship it is possible to trace the curve shown in the Figure 2.10.

Characteristics of materials for performance in fire resistance are given in EN 13501-2 [37]. For non-load bearing elements, the important classifications are: Integrity (E), Insulation (I), Radiation (W) and Mechanical Action (M). The test for the partition type element is defined by EN 1364-1 [38] and the results are presented according to the classification letter followed by the time, in minutes. The performance criteria are exposed on Table 2.13.

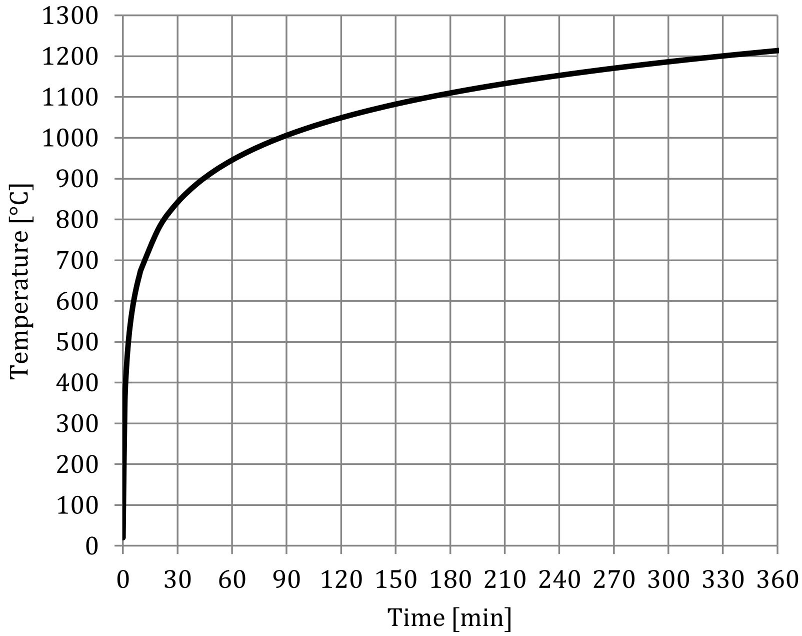


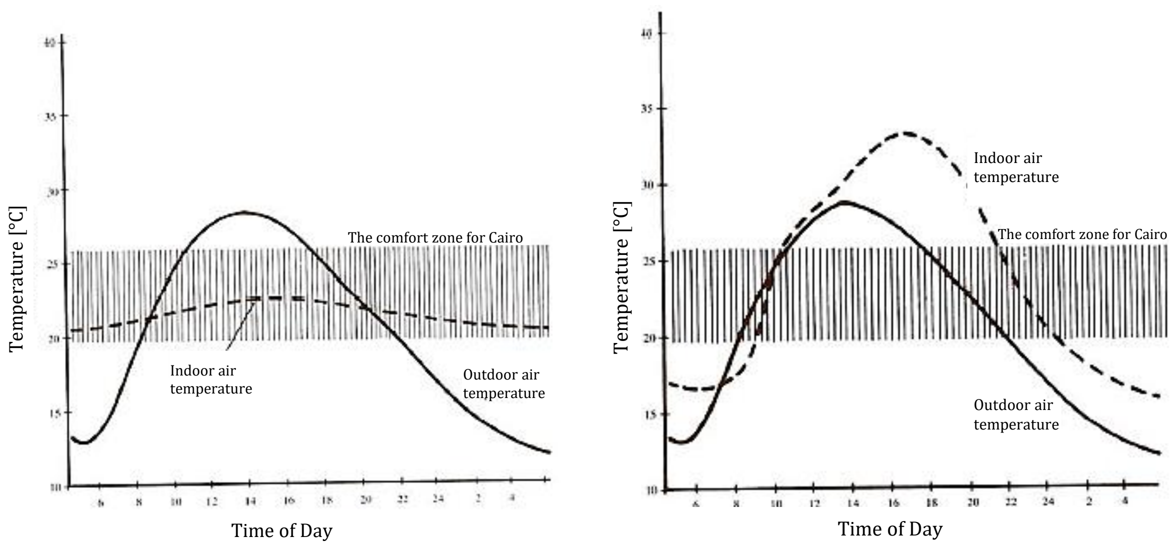
Figure 2.10: Standard Curve ISO.

Table 2.13: Performance Criteria of Non-Load bearing Elements – Partitions (adapted from [37]).

Classification	Analysis
E	Cracks or opening in excess of given dimensions; Ignition of a cotton pad; Sustained flaming on the non-exposed side.
I	Average temperature rise of the unexposed face, limited to 140 °C and maximum of 180 °C above initial average temperature.
W	Does not exceed 15 kW/m^2.
M	The element shall resist the impact without prejudice to the E and/or I performance.

It is expected that the building materials have good thermal behavior to reduce energy losses and maintain the environment with temperatures in good conditions. The materials are more efficient as the lower thermal conductivity, which corresponds to the higher thermal resistance and the lower thermal transmittance [5].

However, the walls constructed of adobe have high thermal conductivity ($\lambda \simeq 1.5$ W/(m·K)), which leads to other explanations for the good behavior of this material as a heat moderator [39]. The interpretation for this phenomenon can be explained by high thermal inertia that the earth presents, enabling this heat exchange through store and release [5]. The heat exchange of this type of construction is related to the amount of air and water in the bricks, these air pores form a thermal insulation and the stored water is released when the temperature is too high favoring its decrease [39], [40], as shown in Figure 2.11, which compares the indoor and outdoor air temperature of walls in adobe and prefabricated concrete.



(a) Adobe (b) Prefabricated Concrete

Figure 2.11: Comparison of Indoor and Outdoor Air Temperature Fluctuations within a 24 Hour [41].

2.7 Soil-Cement Blocks with Additions

After the addition of stabilizers, such as cement, to CEB, they gained immensely greater strength and durability to unstabilized CEB. This gain has made it possible now to investigate the addition of other materials that maintain the conditions of use and that make it an even more ecological material. The first residues incorporated into the CEB were inert residues as they did not chemically react with the final composition and could be treated more simply. Currently, the academic community has applied its research efforts with organic waste. Other wastes used are natural fibers, which guarantee stability to the blocks. The aim of this section is to address these additions, based on scientific research, to complete the state of knowledge.

2.7.1 Natural Fibers

The fibers are used in blocks since the adobe needed to be improved through stabilization to avoid retraction cracks and increase tensile and compressive strength [42]. This process has been improved as the technology evolves.

After the adobe, the fibers began to be used in CEB. The study of the addition of natural fibers of coconut and sisal, in a content of 4% allowed the increase of the ductility of the blocks, a characteristic desired in the civil construction. The problem of these fibers is the high water absorption, which reduces the compressive strength. In order to solve this obstacle, the incorporation of asphalt emulsion was efficient, reducing the absorption and thus increasing the strength of the CEB [43]. However, the asphalt emulsion solution is not as ecological as possible.

Sometime later the coconut fiber was investigated in order to evaluate the thermal conductivity of the CEB with addition of this residue, besides other properties such as weight, density and compressive strength. The addition of fiber resulted in lower block weight and lower density. The consequence of the decrease in density was the lower compressive strength, however, most of the specimens remained within the standard used. Regarding thermal conductivity, the study showed that the addition of coconut fiber decreases by about 50% relative to the standard specimen, and this result is extremely satisfactory, since it enables energy economy [44].

Another fiber used in CEB was the rice husk. In this study it was proposed the solution of wrapping them in lime solution to improve adhesion in the soil-cement mixture. The tendency was to decrease the compressive strength and the specific mass, and increase the water absorption and optimum moisture of the mixture. By fixing the minimum compressive strength to 1 MPa, the observations were that, even with these negative points, the possibility of using 20% cement substitution per rice husk was not discarded, because in these percentages the current standards were met [45].

More research with rice husk in CEB was made, in 2008 researchers replaced percentages of the cement by rice and brachiaria husks, both agricultural residues. In this research, like in the previous one, lime solution to treat the residues, was used. The analysis of the physical properties of the local soil showed that this was not suitable for the production of CEB, soon it was added fine sand for granulometric correction. Water absorption and simple compression strength tests were performed in the cylindrical blocks. The addition of 10% rice husk was the treatment that provided the best result, with 2.11 MPa at 7 days age, being according to the standards used, but the values reached by this treatment did not exceed CEB without addition [46].

Another study with the same agricultural wastes, rice and brachiaria husks, was carried out in sequence of the previous one. Besides the already known result of other studies of the decrease in compressive strength, it was observed that the rice husk increases the deformation of the blocks, which may aid in the control and monitoring of cracks that arise [47].

Mechanical and thermophysical analyses were performed to characterize CEB and walls by Marques et al. [48], also using rice and brachiaria husks. The replacement of 10% of the cement per rice husk was the only one that presented compression strength within the pattern established by standards. This percentage of replacement (10% rice husk) was also the one that presented the best thermal behavior, the treatments presented values between 0.35 and 0.38, which are lower than required by the used standard (0.70 to 1.05) explaining the good behavior of this material for thermal comfort.

Within the residues of construction it is also possible to find fibers; the wooden ones are an example. These fibers were studied as CEB addition, as a partial substitute of the soil, ranging from 1.5% to 6.5%. Simple compressive strength and flexo-traction tests were performed, and even though the blocks with residues had lower results than the ones without residues, it was observed that when the blocks were demolded after 24 hours of confection their mechanical characteristic had a behavior similar to the ordinary CEB, and they presented smaller variations in relation to the demolded ones immediately, as indicated by the standard used [49].

Another example of fiber found in construction waste is Kraft paper fiber, found in cement bags. In order to obtain more resistant CEB and to reduce the amount of wasted material, bricks and walls of soil-cement with addition of these fibers, called, Kraftterra were manufactured. As the fibers would absorb a lot of water, in the recycling process Aloe Vera sap was added so that the absorption was at acceptable levels. The results obtained were satisfactory, since Kraftterra reached higher values of compressive strength than conventional CEB, even after aging cycles by wetting and drying. In addition, the blocks with fibers had ductile behavior, as well as other studies with previously cited fibers [50].

Mostafa and Uddin [42] developed research using banana fibers in the CEB to examine flexural and simple compressive strength. These fibers have high tensile strength, weak point of the earth, and are discarded as agricultural waste. The study evaluated the behavior of the blocks with fibers in 6 different sizes, comparing them with blocks without fiber addition, all blocks contained 7% of cement. The results of the addition of fibers were superior in about 70% and 80% in the compressive and flexural strength, respectively, evidencing the favorable use. In addition, the blocks with fibers had gradual rupture while the ordinary ones rupture suddenly.

Studies with rice husk are still analyzed, and over the years, improved. In the year 2017, an Artificial Neural Network (ANN) was used as a tool to aid in data analysis, through MATLAB software, where the results were separated by similarity according to established input parameters. With the grouping of the system it was possible to observe that when a content of 10% of cement was used in the CEB, any content of rice husk could be incorporated into the mixture without prejudice to the final resistance, that is, the blocks met the standard [51].

2.7.2 Construction and Demolition Waste

Construction and Demolition Waste (CDW) are the inorganic materials most widely used for additions in bricks and blocks, among which are residues of mortar, concrete, ceramics, marble and granite. Studies about the addition of these wastes make it obvious that they are more than just debris and can be widely availed without causing injury and sometimes even improving the final composition.

Using recycled aggregates for the preparation of CEB, in proportions of substitution of natural aggregate from 0% to 85%, and cement content fixed at 12%, allowed to achieve satisfactory results. With higher compressive strength, lower water absorption percentages and mass losses within the established limits. It was found that the optimum recycled content varies between 50% and 75% to obtain values that fit within the standards used [52].

One of the CDW is the mortar, the addition of this waste was done by Ferraz and Segantini [53] in the CEB and the results of the mechanical properties proved to be better than that of the ordinary CEB. The addition of 40% of residue improved the grain size curve, leaving it close to the ideal, allowing decreasing the cement content and decreased the optimum moisture of the final mixture, which makes the final product more economical. Another change caused by the addition of mortar residue was the reduction of liquid and plastic limits, an important contributor to the quality of CEB.

Materials that correct the grain size curve are excellent for lowering the cement content in the CEB. This was the intention of the study that added quarry fines (or stone powder) in the CEB. With cement content in 5%, it was possible to obtain resistant blocks above the normative requirement, that is, at least 2.1 MPa. It was found that as the residue level was increased the compressive strength was also increased, which decreased the energy incorporated in the process, due to the possibility of using lower cement content, and became more economical [54].

The residues besides correcting the grain size curve also help in the decrease of the plasticity index, and consequently the dimensional variations. This fact was observed when marble and granite beneficiation was used in CEB. Simple compressive strength analysis showed that with 15% of cement, and any residue percentage, the bricks could be used in structural masonry, that is, values of compressive strength above 4 MPa at 7 days curing. Water absorption values did not change significantly as the residue content was increased; all were within the limit [55].

The investigations of CDW added to the soil-cement even use the part of the residue of the concrete. These wastes showed to be suitable for use with cement economy. The conclusion that there is an optimum residue addition content between 40% and 60% occurred in the analysis of the compressive strength result, and with a cement content of 6% it is possible to obtain favorable results, above 2 MPa [56].

With the incorporation of granite residues in CEB, Lima [57] evaluated the durability of the blocks and compared them with blocks without additions. The evaluation was through to loss in mass and volume variation. When specimens were not brushed, as indicated by the standard used, the values were always below the indicated limit, but when they were brushed, the mass loss and volume variation are much higher than the specifications. That makes it possible to say that the main factor for increasing aging is brushing. However, there was an increase in compressive strength after the aging cycles.

CEB were manufactured using manual press and with addition of CDW in up to 100% replacement of the soil fraction without loss of quality in the final product. The increase of residue showed good performance regarding retraction, which had a significant decrease. Soil replacement by CDW proved to be effective in decreasing cement content. CEB reached strength above 2 MPa, minimum required value, with only 4% of binder, proving to be a potential material to be used [58].

When the soil is not suitable for the production of CEB, it may be composed of sand and clay in suitable proportions. A Colombian study added that the CDW replaced only part of the sand, using the clayey part of the local soil. Clearly, CDW blocks were superior in compressive strength, above 2.91 MPa, and abrasion resistance, above 3.25 MPa with a minimum coefficient of abrasion equal to 10.80 cm^2/g, than CEB without residues. The blocks with 70% of CDW obtained good results for water absorption by capillarity and all the blocks with CDW presented less cracks than the traditional blocks [59].

In Brazil researchers used municipal pavers waste, in 30% content, for application in CEB. This material improved the physical properties of the natural soil, one of the contributing factors to obtain better results, such as better grain accommodation, lower optimum moisture content, lower water absorption and, consequently, better simple compression strength [60].

2.7.3 Residual Ash

Agricultural wastes after a fire treatment form mineral ash with high concentration of silica (SiO_2). These ashes have been discarded for years until it was seen its potential use in civil construction, in order to cheapen and improve the properties of the materials. As soil stabilization is more used in the paving area, this was one of the first to use ashes, such as Rice Husk Ash (RHA) [61].

Not all burning of agricultural waste is controlled, so some generate ashes with little or no pozzolanic activity. In 2008, a research was conducted using RHA without pozzolanic activity in CEB. However, such material is extremely thin, having served filler, partially replacing the soil of the composition. Was established a minimum of 1 MPa for compressive strength at 7 days, which was met by most compositions. Thermal conductivity and specific heat were also evaluated, and were similar to previous studies, used for comparison. For the durability, wetting and drying tests were done according to Brazilian Standard, with modification of the brushing step, which according to the authors is not the most important step when studying blocks for use in masonry, where abrasion is little requested [62].

Additionally to agricultural waste, the process of thermoelectric plants also form residual ash, known as fly ash. The use of fly ash was performed with good results for both individual blocks and masonry prisms. The minimum compressive strength obtained was 4.9 MPa with CEB in saturated condition, reaching 12 MPa of average, in dry condition. For the masonry prisms a compression ratio of 0.38 and 0.39 times was found for the individual blocks, indicating that the standard used overestimates the compressive strength of the masonry walls, suggesting that 0.5 times the resistance of the blocks. Another important result is the shear strength of the prisms, with crushing where there were higher levels of pre-compression, which indicates, according to the authors, excessively stiff and the use of dry joint is not the most adequate solution, and the use of mortar can improve this situation [63].

Caldera ashes are a residue resulting from biomass burning, and just as RHA was studied for addition in soil-cement. The blocks were made by a manual press and cured in an uncontrolled environment, watered 3 times a day. In this study the blocks did not reach sufficient strength to be used, it was below 2 MPa, minimum value required. Such fact according to the authors is due to the great climatic variation of the region [64].

2.7.4 Organic Waste

The addition of organic materials to building materials is rarely employed, even because though many standards limit the percentage to a very low level. Still some researchers try this addition since the consumption of raw materials by the civil construction is high as well as the urban waste generated.

A group of researchers evaluated the growth of fungi in building blocks with the addition of sand and sludge from a Wastewater Treatment Plant (WWTP). The blocks were crushed and put in different environments, with and without treatment, where fungi growth was analyzed. One of the conclusions of the authors is about the importance of the hygroscopic effect, since there was no fungus proliferation in the crushed and dry materials, only when it contained some humidity, thus showing the importance of the blocks porosity and their capacity of water absorption [65].

A work done in 2017 for the production of CEB with malt marc, showed fungal growth in the blocks during the cure time, as shown in Figure 2.12, the high organic matter content is the explanation for this fact. The appearance of these fungi contributed to larger amounts of cracks in the blocks. As the blocks were too compromised, their results were far below what is expected for a masonry block [64].

Figure 2.12: Brick with Fungal Growth [64].

2.7.5 Other Wastes

In addition to CDW, other wastes such as mechanical turningin are used in the manufacture of CEB. As in the case of the study that with the addition of 15% of this residue was able to make blocks that were better than those without addition. In order to produce the CEB, there was first a need for grain size curve correction of the local soil, since this did not meet the requirements for good production. For that, 40% of sand was added. Some failures in the production and local climate did not favor the results. However the blocks with residues were shown superior to the conventional ones, needing more studies to make feasible the use [66].

Although not exactly a waste, the wooded hill of termite is a nuisance to pasture areas. One research sought to compare the CEB produced with *Neossolo Quartzarênico* and with wooded hill of termite, before the production every organic part was removed. The bricks were evaluated for water absorption and simple compression strength. For bricks with wooded hill of termite, there was a decrease in absorption between the cure ages of 7 and 28 days, which is a good result, because it usually corresponds to a strength gain, which was noticed when tested [24].

Chapter 3

Materials Properties

The studies presented in the previous chapter show the importance of the choice of materials. In order to obtain the necessary knowledge about the CEB, it is first necessary to know the materials that comprise it, such as: soil, cement, water, silica and municipal waste. In this chapter, the physicochemical properties of these materials will be presented. Scientific research was done on the materials used, in addition to data collection provided by the manufacturers, and conducting characterization tests, which were carried out in the Geotechnics Laboratory of the School of Technology and Management (ESTiG) at the Polytechnic Institute of Bragança (IPB).

3.1 Soil

Aiming that there is no interference in the results besides the future addition in the CEB, it was decided to use artificial soil. However, the composition choice that approximates the natural soil type was made with caution. In the northern region of Portugal there is a predominance of soils resulting from the decomposition of granite rocks, known as granitic residual soil; to obtain it were combined sand and kaolin, in proportions of 70% and 30%, respectively.

3.1.1 Kaolin

The kaolin used is Mibal, from Barqueiros, kept in bags of 20 kg. In the technical file, which came with the product, show the properties that are in Tables 3.1 and 3.2, it is possible to notice that kaolin has a high concentration of silico-aluminous material. This pozzolanic material in the presence of water reacts chemically in a similar way to cement, forming the same hydration compounds [67], which results in better hydration of the mixture, favoring gains in strength and durability.

Table 3.1: Physical Properties of Kaolin (adapted from [68]).

Properties	Value	Unit
Moisture	<2	%
Density	2.4 to 2.7	g/cm^3
Granulometric Distribution		
<30 μm	99 ± 3	%
<10 μm	92 ± 3	%
<5 μm	81 ± 3	%
<2 μm	68 ± 3	%

Table 3.2: Chemical Properties of Kaolin (adapted from [68]).

Element / Property	Symbol	Value	Unit
Silicon dioxide	SiO_2	46.43	%
Aluminum oxide	Al_2P_3	35.66	%
Iron (III) oxide	FeO_3	1.02	%
Calcium oxide / Quicklime	CaO	0.04	%
Magnesium oxide	MgO	0.12	%
Sodium oxide	Na_2O	0.06	%
Potassium oxide	K_2O	1.22	%
Titanium dioxide	TiO_2	0.26	%
Loss on ignition	L.O.I	15.0	%
Potential of hydrogen	pH	5 to 8	-

3.1.2 Sand

The sand was acquired in the region, and before being used it was dried and kept in a protected place of humidity.

A test was carried out to determine the volumetric mass of the sand according to NP 954 [69] and the result was 2.58 g/cm^3.

3.1.3 Soil Characterization

Physical analyses were carried out in the soil (sand and kaolin) to obtain granulometry, liquid and plastic limits and plasticity index.

The granulometric evaluation was carried by wet sieving according to LNEC E 239 [70], in which it was possible to obtain the grain size curve presented in Figure 3.1. The results of liquid and plastic limits were carried out for the soil sample, as indicated in NP 143 [71], for the liquid limit test it was possible to obtain the curve indicated in Figure 3.2, and the values in Table 3.3 that present also the plastic limit and plasticity index.

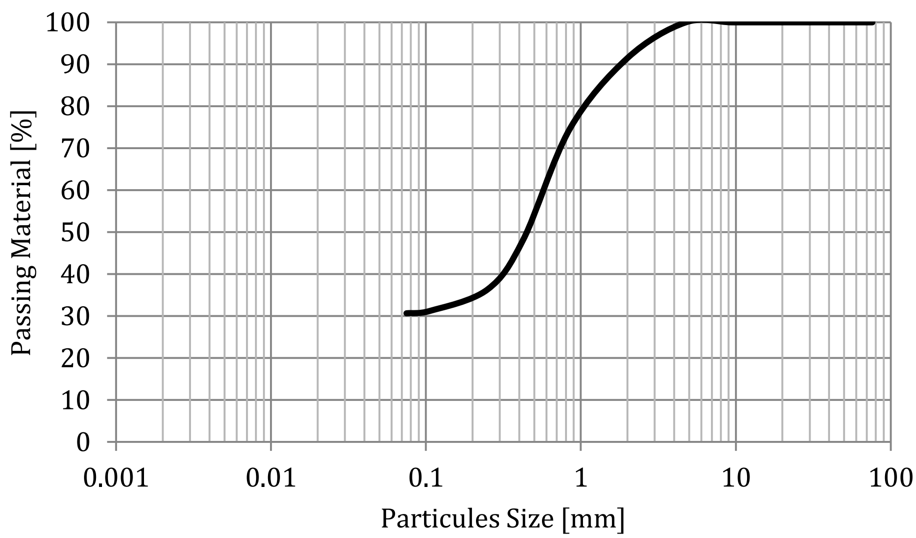


Figure 3.1: Grain Size Curve.

Table 3.3: Soil Consistency Limits.

Consistency Limits	Value	Unit
Liquid limit	43.5	%
Plastic limit	25.8	%
Plasticity Index	17.7	%

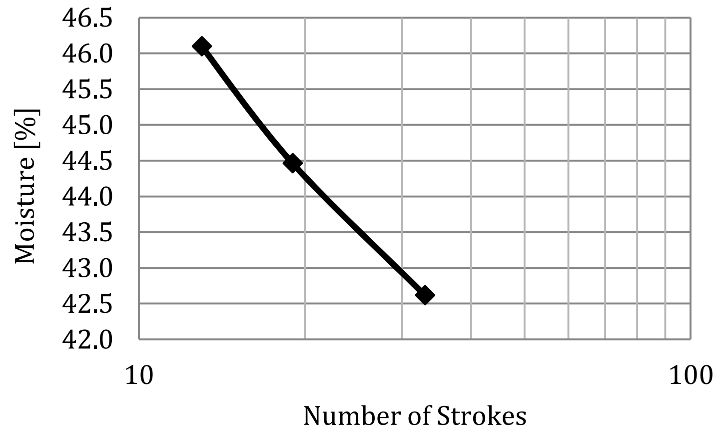


Figure 3.2: Liquid Limit.

After these analyses it was possible to classify the soil. The mixture of kaolin and sand allowed obtaining soil Clayey Sand (SC), according to the unified classification of soils American Society for Testing and Materials (ASTM) D 2487 [72] and A2-7 according to the classification AASHTO M 145-91 [73].

In order to verify if the soil chosen is in accordance with the standards used, comparisons of the soil analysis were made with the normative requirements presented in Chapter 2, Table 2.1 and Figure 2.9.

The standard LNEC E 197 [74], whit heavy compaction was used, where the Maximum Dry Unit Weight (γ^{d}_{max}) and the Optimum Water Content (ω_{opt}) for the soil was obtained, as shown Figure 3.3.

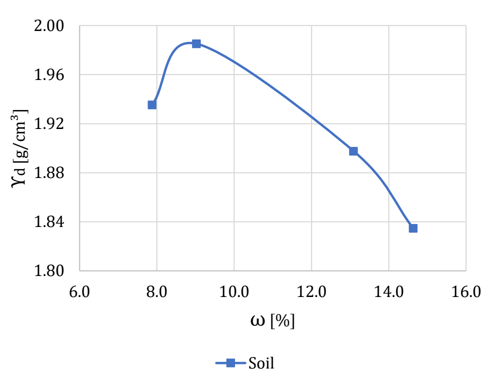


Figure 3.3: Proctor Compaction of the Soil.

3.2 Cement

The cement used in the stabilization of the CEB is SECIL brand; type CEM II / B-L 32.5 N, its choice was due to local availability and indication for use in soil-cement. It is supplied in 25 kg bags and the characteristics provided by the manufacturer are shown in Table 3.4.

Table 3.4: Cement Characteristics (adapted from [75]).

	Specified Value	Performance	Unit
Composition			
Clinker	65 to 79	-	%
Limestone	21 to 35	-	%
Other constituents	0 to 5	-	%
Chemical properties			
SO_3 content	≤ 3.50	Conform	%
Chloride content	≤ 0.10	Conform	%
Physical properties			
Initial setting	≥ 75	Conform	min
Expandability	≤ 10	Conform	mm

The cement characteristics presented in Table 3.4 can be compared with the cement recommended for soil-cement presented in Tables 2.2 and 2.5. The comparison makes it clear that the chosen cement meets the standards.

3.3 Waste

The municipal wastes, from the organic fraction of urban solid waste, used during the research come from the company Resíduos do Nordeste, located in Mirandela. The waste is collected by the company in the region and data show that they are produced on average 140 tons/ day [76].

With the waste provided for the research, a technical file was sent with its indicative composition. Table 3.5 shows the results obtained after the waste treatment.

Table 3.5: Indicative Composition of the Waste (adapted from [77]).

Component	Value	Unit
Moisture	29.6	%
Organic matter	48.8	%
Organic carbon	27.1	%
Nitrogen (N)	1.3	%
Phosphorus(P_2O_5)	1.1	%
Potassium (K_2O)	1.4	%
Calcium (Ca)	4.9	%
Magnesium (Mg)	0.8	%
Sulfur (S)	0.6	%
Boron (B)	43.4	mg/kg
Cadmium (Cd)	0.9	mg/kg
Chromium (Cr)	130	mg/kg
Copper (Cu)	209.7	mg/kg
Mercury (Hg)	0.4	mg/kg
Nickel (Ni)	49	mg/kg
Lead (Pb)	110	mg/kg
Zinc (Zn)	453	mg/kg
Salmonella spp.(Fresh matter, 25g)	Absent	-
Escherichia coli (Fresh matter)	460	n°/g
Weed plants (Fresh matter)	0	-
Anthropogenic inerts	0.7	%
C/N ratio	20.9	-
Density	0.45	g/cm^3
Electrical conductivity (Fresh matter)	2.5	mS/cm
pH (Fresh matter)	8.0	-

The wastes provided did not undergo any selection or granulometry control, and were used in the same way that they were received. Its appearance can be seen in Figure 3.4.

3.4 Water

The water used comes from the public supply network of Bragança.

Figure 3.4: Municipal Waste.

3.5 Silica Fume

Silica is a powdery material, which generates physical and chemical effects on the cement matrix. The filler effect, helps to increase the attraction between the particles, this is the physical effect. The chemical effect is the pozzolanic reaction of the transformation of CH (calcium hydroxide), brittle material, in C-S-H (hydrated calcium silicate), resistant product responsible for adhesion [78].

In a study carried out in Turkey with the addition of Silica Fume (SF) in concrete, a significant decrease in water absorption was observed when a content of 10% of SF was used [79]. It is also known that SF improves compressive and tensile strength and abrasion resistance, reduces creep, decreases permeability and produces more resistance to attacks by sulfates and chlorides [78].

The properties exposed about the silica were the reason for the choice of material for addition in the soil-cement block. With this incorporation is expected the pore reduction and consequent increase of the strength. It is still expected that the greater compactness of the mixture will prevent the proliferation of fungi caused by the added organic compound as occurred in a previous study cited (see Figure 2.12).

The silica used is the MAPEI brand, chemical characteristics of the product were provided by e-mail by the company, and are specified in Table 3.6. Other properties, shown in Table 3.7, are available on the company's website.

Table 3.6: Chemical Composition of Silica Fume. [1]

Composition	Value	Unit
CaO	1.08	%
SiO_2	89.79	%
Al_2O_3	0.17	%
FeO_3	0.17	%
K_2O	0.39	%
MgO	0.14	%
Na_2O	0.55	%
TiO	0.01	%
P_2O_5	0.07	%
MnO	0.02	%
PR	6.40	%

Table 3.7: Product Identification [80].

Product Identity	Result	Unit
Consistency	Powder	-
Colour	Dark grey	-
Mass in pile	600	kg/m^3
Main action	Pozzolanic	-
Secondary action	Filler	-
Dry solids content	100	%

[1] Chemical composition sent by the company by e-mail.

Chapter 4

Experimental Program

This chapter will present the methods and equipment used for the manufacturing of soil-cement cylindrical specimens. Therefore, it will be approached the determination of the most suitable proportions for the specimens manufacturing, their manufacturing process and tests for analysis, being: water absorption by immersion, durability by wetting and drying cycles, simple compressive strength and compressive strength under effect of high temperatures. All tests were carried out at the Geotechnics or at Structures and Resistance of Materials Laboratories at ESTiG.

4.1 Preliminary Tests

The preliminary studies allow to obtain the best proportions and the main aspects that influence the quality of the soil-cement blocks. Thus, some tests were made that enabled the appropriate choices that were used in the sequence of this dissertation.

The adequate water content is essential for adequate production of CEB, so the standard Proctor compaction test was one of the first to be performed. As for the soil composition, Proctor compaction was done for soil-cement mixture, using LNEC E 197 [74], with heavy compaction, the γ^d_{max} and ω_{opt} were determined. Results are shown in Figure 4.1.

The ω_{opt} of SC_{10} (Soil whit 10% of cement) was also used for waste compositions, which were made by replacing 10% and 20% of the volume of sand.

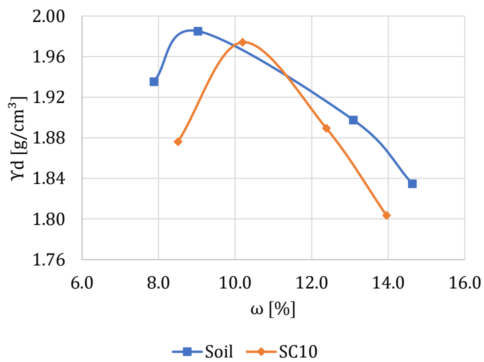


Figure 4.1: Proctor Compaction.

Test specimens were prepared for compression testing. During the demolding, it was verified that specimens containing 20% of residues disintegrated but for specimens containing 10% of residues this problem did not occur, this fact indicated that the incorporation of residues in the mixture modified the optimum water content, which means higher amount of waste, greater the impact on the moisture.

An initial solution to this problem was the unmolding 24-hour after the manufacturing process, which worked, that is, the specimens did not disintegrate, but it was not the most practicable solution, since the molds were few and while they were occupied with these mixtures, it was impossible to make other. It was then proposed to pre hydrate the cement, which was not efficient and brought less compressive strength of the specimens.

As the specimens were not completely regular, the interference that the covering of the blocks caused in the compressive strength was tested. No significant changes were noticed, so it was decided not to perform this step, as it caused friction and could impair its resistance.

The organic compound released a bad smell so activated charcoal was added to the composition. The method consisted of mixing the two materials in different proportions and different control means, among which: open-air, in stove and isolated. The best result was in the proportion of 1:2 (2 parts of residue for each part of activated charcoal), with relatively small amounts, which were not made feasible by the amount that was required per specimen. Another factor for which the experiment was not continued refers to the price of activated charcoal, which makes the final product with higher value incorporated, which is the opposite of that expected in the production of CEB.

At the end of the preliminary tests, decisions were taken on the follow-up of the study. The use of 10% of waste was discarded, since the resistance was very close to those that contained 20% and made possible better use. With the use of 20% waste the need to carry out a Proctor suitable for such composition was found. The pre hydration of the cement was also ruled out of use because it did not help the resistance. Besides the non-continuation of the use of activated charcoal.

4.2 Proportions

The definition of the quantities of materials to be used was based on the initial tests and the studies mentioned in the previous chapters.

The cement content was set at 10% relative to the mass of dry soil, or mixture of soil and residue. This value is widely used and complies with the standards presented in Chapter 2. When using silica fume, it replaces 10% of the cement mass. The determination of this percentage was based on studies [78], [81].

It was decided to evaluate the effects of the addition of the organic compound on two compositions, with and without SF, and to compare the results with a reference composition, with soil and cement only, the mass percentages used are presented in Table 4.1. The nomenclature of the compositions was chosen to facilitate identification. For example, $SC_{10}R_{20}Si$, S is used for soil, C_{10} represents cement and its respective percentage of 10%, R_{20} indicates the 20% residues used and finally Si for silica.

Table 4.1: Mass Proportions of CEB.

	Soil		Residue	Cement (to the soil/ soil	Silica + residue mass)	Unit
	Sand	Kaolin				
Soil	70	30	-	-	-	%
SC_{10}	70	30	-	10	-	%
$SC_{10}R_{20}$	63.32	33.92	2.76	10	-	%
$SC_{10}R_{20}Si$	63.32	33.92	2.76	9	1	%

Once the percentages of wastes were established, a new Proctor compaction was carried out, where the γ^d_{max} and the ω_{opt} for the composition with waste were determined and are presented in Figure 4.2, together with the previous results. It is possible to note a significant decrease of γ^d_{max} with the inclusion of the residues in the composition, this may be indicative of subsequent loss in compressive strength. One positive point that can be noticed is the decrease in ω_{opt}.

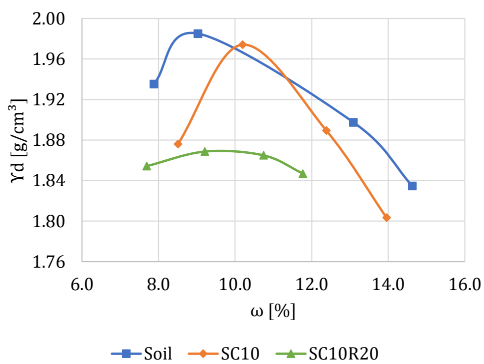


Figure 4.2: New Proctor Compaction.

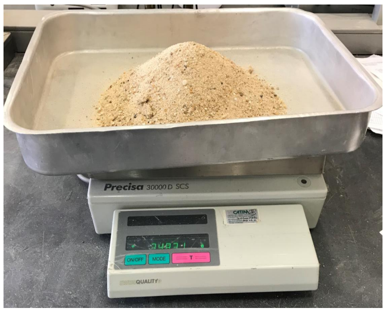
With the results shown and analyzed, the manufacturing processes of the specimens started.

4.3 Manufacturing Process

The manufacturing process can be divided into three parts: preparation, compaction and cure. A total of 143 specimens were manufactured.

4.3.1 Preparation

The preparation of the specimens begins with weighing of each part that composes it (Figure 4.3a) until they are all together, as shown in Figure 4.3b. Afterwards all dry material (soil, cement and waste) is mixed manually until it reaches homogeneity, as in Figure 4.3c. Finally the water is added in the optimum amount determined in the Proctor compaction, according to the composition being prepared. Again it was mixed until the moisture was evenly distributed and there were no more agglutinations (Figure 4.3d).



(a) Weighing

(b) CEB Materials

(c) Dry Mixture

(d) Moisture Mixture

Figure 4.3: Preparation Process.

4.3.2 Compaction

The compacting process occurred as soon as possible after mixing was homogenized in order to avoid loss of moisture. Cylindrical metal molds with 70 mm diameter and 140 mm height were used, respecting the indication given by standard ASTM D 1632 [82], length equal to twice the diameter.

The compacting was performed using the equipment shown in Figure 4.4a, divided into three approximately equal layers with fifteen strokes per layer, where a manual compactor was always dropped from the same height (Figure 4.4b).

Following compaction, the specimen was removed from the mold. For this, a hydraulic jack was used, shown in Figure 4.5a. Figure 4.5b shows a demolded specimen next to one of the molds.

(a) Compaction Equipment (b) Compaction

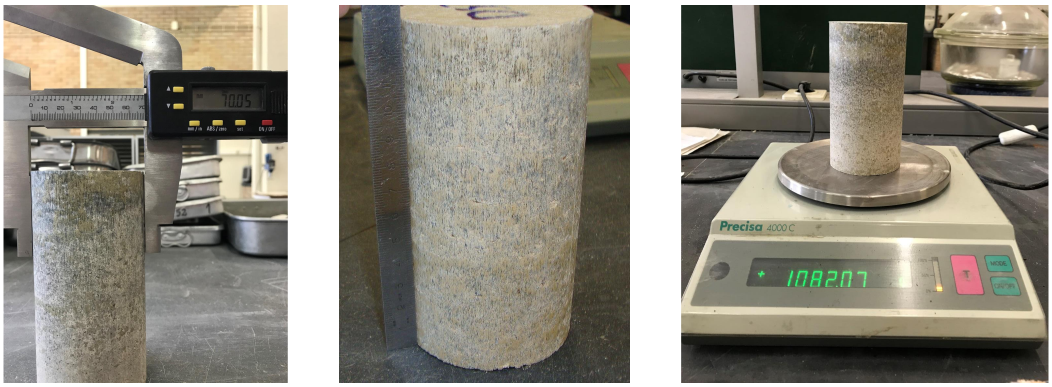
Figure 4.4: Compaction Process.

(a) Hydraulic Jack (b) Demolded Specimen

Figure 4.5: Demolding Process.

In order to differentiate the type of test that will be performed, the specimens were designated by the prefixes: A for the absorption tests, D for the durability tests, C for the compression tests and F for the tests submitted at high temperature. To distinguish the compositions with residue, in addition to the letters of the tests, the specimens were designated by the suffixes R and Si for the compositions without and with silica, respectively. For example the nomenclature ASi refers to a specimen which will be subjected to water absorption test of the composition containing silica. The compositions without residue or silica received no further differentiation beyond the letter of the test. After the designs were made, measurements could be taken.

Measurements were carried out with the aid of a caliper (Figure 4.6a) and a ruler (Figure 4.6b) to measure the diameter and height, and a balance to verify the weight of each specimen, as in Figure 4.6c. After that, it was passed to the last stage of manufacturing.



(a) Caliper (b) Ruler (c) Balance

Figure 4.6: Measurements.

4.3.3 Cure

The specimens were cured in a controlled environment, a humid chamber with a mean temperature of 20 °C and a relative humidity of 95%. The cure time was given until the day each specimen was assayed.

4.4 Water Absorption

The immersion absorption tests followed the recommendations of NBR 8492 [83]. Therefore, the specimens were dried in a stove with a temperature between 105°C and 110°C until a constant mass was reached, which allowed to obtain the dry mass of the specimen, M_1.

Then the specimens were completely submerged in water for 24 hours, as shown in Figure 4.7. Always taking care not to mix the compositions with and without residue so that there is no interference. After 24 hours the specimens were surface-dried and weighed, therefore obtaining the saturated mass, M_2.

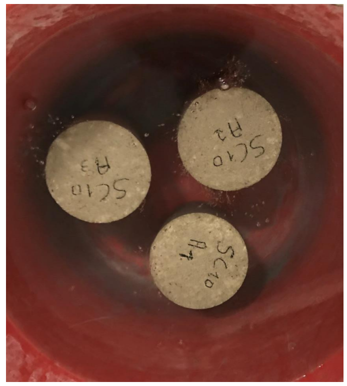


Figure 4.7: Immersion of Specimens.

With the masses, dry and saturated, the water absorption (A), in percentage, of each specimen was calculated by equation 4.1, the result is given by the average of three specimens.

$$A = \frac{M_2 - M_1}{M_1} \cdot 100 \tag{4.1}$$

The tests were performed at 7 and 28 days of cure. After testing, the 7-day specimens returned to the humid chamber until they reached 28 days of age, this is the T1 condition. The T2 condition refers to the specimens that were tested for absorption at 28 days of cure. All were tested for compressive strength in a saturated condition after the 28-day curing absorption test.

4.5 Durability

The durability test was carried out with the purpose of verifying the volume variation and the loss of mass of the cylindrical specimens when submitted to accelerated aging, by wetting and drying cycles according to NBR 13554 [30]. For the test, three specimens are required for each composition to be analyzed. The first, specimen 01, measures the volume variation, while with the other two, specimens 02 and 03, are measure the loss of mass.

From the mixtures made, samples were taken to measure the initial moisture, which was calculated according to equation 4.2, where ω_0 is the initial moisture calculated in percentage, M_w is the mass of the water and M_s is the mass of the dry soil. Soil moisture was compared to the optimal moisture, and according to NBR 12024 [84] the difference between them can not be greater than ±5 percentage points.

$$\omega_0 = \frac{M_w}{M_s} \cdot 100 \tag{4.2}$$

The Dry Unit Weight (γ_d) actually achieved was also calculated, and the Degree of Compaction (DoC) of each composition, which should be between 98% e 102%, according to NBR 12024 [84].

$$\gamma_d = \frac{\gamma}{\omega_0 + 100} \cdot 100 \tag{4.3}$$

Where γ is given by equation:

$$\gamma = \frac{M}{v} \tag{4.4}$$

Where M is a total mass of the specimen and v is the volume.

$$DoC = \frac{\gamma_d}{\gamma_{max}^d} \cdot 100 \tag{4.5}$$

After demolding all the specimens, the initial measurements were taken, then all the specimens were taken to the humid chamber. Afterwards 7 days the cycles began, with weighing and measurement of the specimens, which were soon taken to immersion for 5h, as shown in Figure 4.8, taking care not to mix the compositions with and without residue. After the immersion period the specimens were dried on the surface and again the measurements and weighing were carried out and then taken to the stove, where the temperature remained at ±71°C for 42 hours, see Figure 4.9. When cooled, the specimens listed, 02 and 03, underwent brushing and then again the measurements and weighing of all specimens were performed.

Figure 4.8: 5-hour Immersion.

Figure 4.9: Stove.

The above procedure was repeated five more times, in a total of six wetting and drying cycles, where at the end of these cycles the specimens were stove dried at a temperature between 105°C and 110°C until a constant mass was reached.

With the data of each step "n" it was possible, through equation 4.6, to calculate the volumetric variation occurred in the specimen 01.

$$V_{v,n} = \frac{v_0 - v_n}{v_0} \cdot 100 \tag{4.6}$$

In order to know the mass loss of the remaining specimens, it was necessary to calculate the amount of water retained (W) in specimen 01, which followed the relationship presented in equation 4.7. The water retained at specimens 02 and 03 is the same, so the final mass of these specimens should be corrected. This correction occurred through equation 4.8.

$$W = \frac{M_{fd} - M_{0d}}{M_{0d}} \tag{4.7}$$

$$M_{fc}^{2,3} = \frac{M_f^{2,3}}{W + 1,00} \tag{4.8}$$

With the corrected masses, the mass loss of the two specimens was calculated, following equation 4.9.

$$L_m^{2,3} = \frac{M_0^{2,3} - M_{fc}^{2,3}}{M_0^{2,3}} \cdot 100 \tag{4.9}$$

The specimens returned to the humid chamber until they were 28 days and then they were tested for compressive strength.

4.6 Compressive Strength

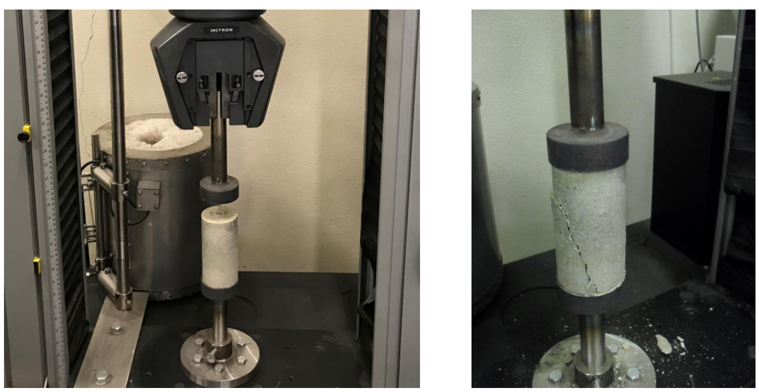
Previous to the beginning of the tests the specimens were measured, height and diameter, and weighed. In general small variations in height and weight were noted during the cure period. The measurements are important to obtain the deformation in the length of the specimen and section of the area in which the force applied by the equipment is distributed. As well as making it possible to calculate the γ of the specimen at the time of the test.

The equipment used to realize the compressive strength is the *Instron*® series 4485, shown in Figure 4.10.

The equipment is connected to a computer where the method used for the test is set, in this case was used a constant speed of force application of 0.6 mm/s, programmed to stop when the specimen collapse. The test input data, such as height and diameter of the specimen, are entered.

For the correct performance of the test, the specimens were properly centered on the test machine and then the approximate upper part of the specimen, as in Figure 4.11a. At the end of the tests the specimens had the appearance as in Figure 4.11b.

Figure 4.10: *Instron*® series 4485.



(a) Test Start (b) End of Test

Figure 4.11: Compression Testing.

The method generates a file with two columns, one with force (F) in kN, another with the extension (δ), in mm, caused in the specimen during the test. With the first column and the area (A) known from each specimen, the compressive stress (σ) was determined through equation 4.10. The second column associated with the initial length (L) known, allowed to calculate the deformation (ϵ) of the specimens, following equation 4.11.

$$\sigma = \frac{F}{A} \tag{4.10}$$

$$\epsilon = \frac{\delta}{L} \tag{4.11}$$

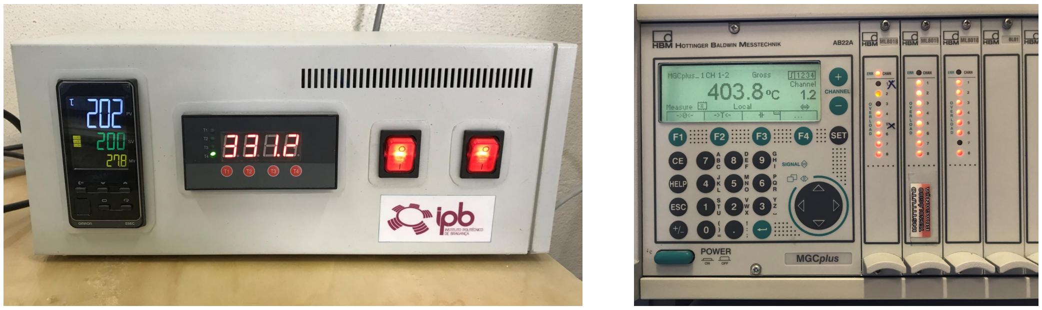
The assays were performed for curing ages of 7, 14 and 28 days for compositions SC_{10} and $SC_{10}R_{20}$ and for the ages of 7 and 28 days for composition $SC_{10}R_{20}Si$. The result of each test was obtained by the average of the specimens, 3 or 4 per test.

4.7 Compressive Strength at High Temperature

Although it is already known that buildings with earth have a good behavior when subjected at high temperatures, the addition of residues can modify this behavior. Therefore, this section will describe the methods used to evaluate soil-cement cylindrical specimens with addition of municipal waste, as to the behavior of compressive strength at high temperatures.

The tests of resistance to compression at high temperatures were carried out for four levels, being 100°C, 200°C, 400°C and 600°C. Where only the mechanical action among the criteria mentioned previously in Table 2.13 will be evaluated. Besides to specimens that were made as reference, F-R, at room temperature, considered 20°C. All tests were done for the 28-day cure time.

To heat the specimens, a Proportional Integral Derivative (PID) type controller (Figure 4.12a) was used to set the desired temperature and maintain it for the time needed for use. For the Data Acquisition (DAQ), MGC Plus (Figure 4.12b) was used, which has 23 channels of reading, of which 2 were used, channel 1.2 to monitor the temperature of the specimen and channel 1.3 that monitored the ambient temperature of the furnace. MGC Plus shares data with the CalmanEasy DAQ Project software, the software performs the time×temperature graph in real time, as shown in the Figure 4.13.



(a) PID (b) MGCplus

Figure 4.12: Heating and Monitoring System.

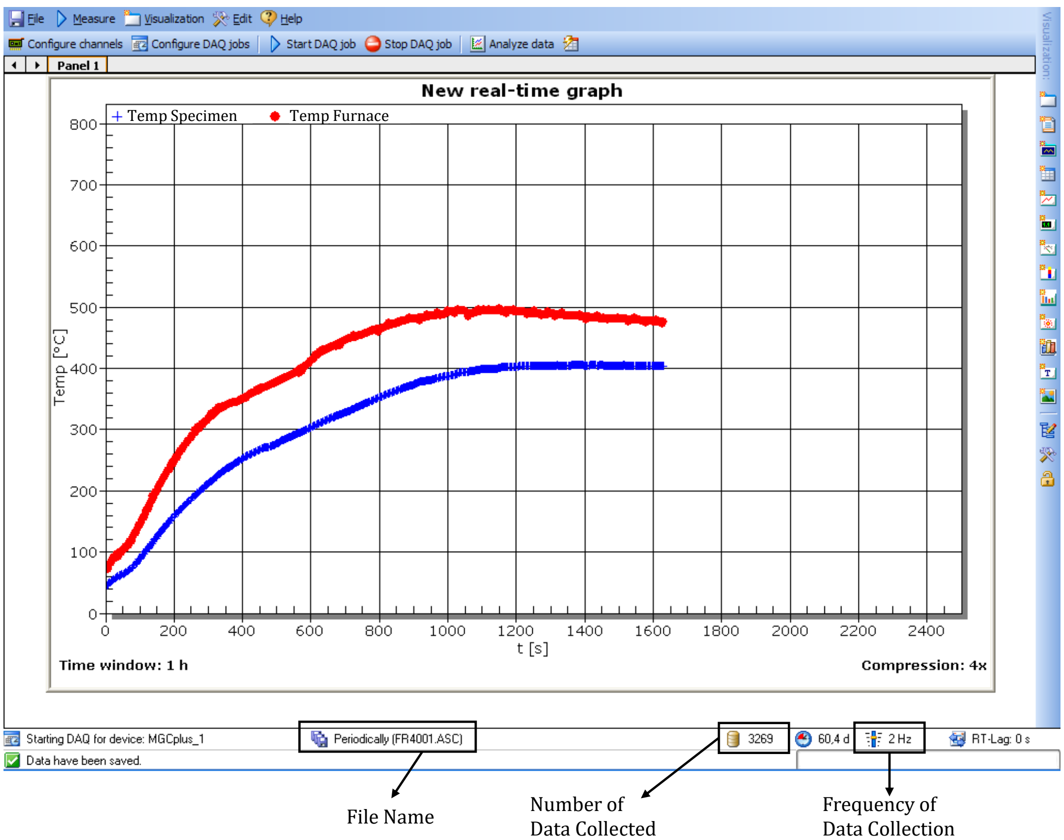


Figure 4.13: Heating Curve.

The tests were performed in a furnace attached to the base to a universal test machine, *Instron*®, adapted to operate under compression, (Figure 4.14). The specimens were fitted to the test equipment as described in Section 4.6. The temperatures were measured with two thermocouples. The first thermocouple was used to control and monitor the temperature of the specimen, while the second was positioned in the specimen surrounding to measure the temperature of the air inside the oven, Figure 4.15.

Figure 4.14: Adapted Furnace.

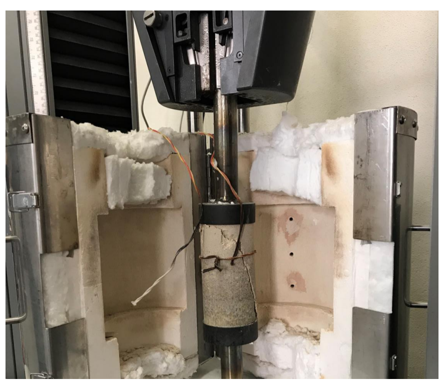


Figure 4.15: Thermocouples.

Previous to start the test, the upper part of the compression equipment should be spaced at a distance by about 5 mm in order to avoid the compressive prestress due to thermal expansion. The furnace was then closed and the PID set to warm it up, at the same time CalmanEasy software was started to read the data and perform the graph that was presented in the Figure 4.13.

When the desired temperature was reached, it was kept constant for 15 minutes.

Waiting time is important to ensure that the internal part of the specimen reaches the same temperature on the outside face, or close enough.

After that the compressive test was started. The procedure to perform the test was to approximate the upper part of the equipment to the specimen, but without making any significant forces, then the same test procedures described in Section 4.6 are carry out. After the specimen rupture, the PID was shut down and CalmanEasy software stopped.

To carry out a new test the furnace should be cooled to room temperature. The average cooling time of the furnace was 1h.

Chapter 5

Results

This chapter is concerns the presentation and analysis of the results obtained in the experimental program regarding water absorption, durability and compressive strength, in which the techniques described in the previous chapters were used. The results will be compared to the standards used and with each other. The effects caused by the cure time will also be evaluated.

5.1 Water Absorption

This section is intended to present the results of water absorption by immersion. The results of 7 and 28 days of cure are presented for the three compositions studied and their respective means. Comparisons are made with the value specified by the standard used.

Absorption values at 7 days are very close for all compositions. At 28 days there are larger variations between the compositions, but still with values not so far away from each other. Table 5.1 shows the values obtained by the three specimens used for each age of cure. Comparing the values obtained with the standard presented in Table 2.3, individual maximum value of 22%, it is noticed that all the specimens meet the requirement with slack.

Table 5.1: Individual Water Absorption.

Composition	07 days			28 days			Unit
SC_{10}	10.97	11.89	11.50	9.02	8.91	9.51	%
$SC_{10}R_{20}$	13.34	12.29	12.49	12.12	12.43	12.38	%
$SC_{10}R_{20}Si$	12.72	12.68	12.07	13.33	13.17	13.47	%

With the individual values for each composition were calculated the means in each age of curing, which are presented in Figure 5.1 and in Table 5.2. In addition to the average, the variation that each composition had between the ages of 7 and 28 days was also calculated.

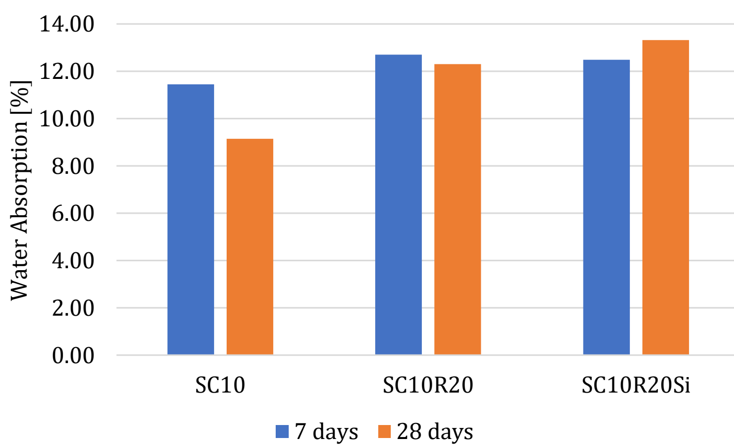


Figure 5.1: Water Absorption.

Table 5.2: Average Water Absorption.

Composition	7 days	28 days	Variation	Unit
SC_{10}	11.45	9.15	-20.14	%
$SC_{10}R_{20}$	12.71	12.31	-3.11	%
$SC_{10}R_{20}Si$	12.49	13.33	6.68	%

The mean values of absorption are well below the 20% specified by NBR 8491 [29], so this is not an impediment to the use of residues in soil-cement blocks.

Only in composition $SC_{10}R_{20}Si$ did absorption increase occur, an abnormal value, since it is expected that with the curing time there will be a decrease the pores and consequently less water inlet. The main reason for this is justified in the organic factor. Organic matter is the main influencing factor in pozzolanic reactions, and organic matter contents above 1% may already cause reaction failures [21], and the pozzolanic reaction being the main reaction of SF, as mentioned in Table 3.7.

Despite higher percentages of absorption and growth with curing time, the composition with silica addition was the one with the lowest variation, that is, it is the most stable composition, where the specimens had values very close with each other.

5.2 Durability

The effects caused by accelerated aging through wetting and drying cycles are presented in this section. The regulatory requirements are evaluated to see if the specimens are or are not in agreement. Visual analyses are presented to verify the appearance of the specimens after the cycles.

At the end of the six cycles of accelerated aging in cylindrical specimens small volume variations were observed, with mean values equal to or less than 1%, shown in Figure 5.2.

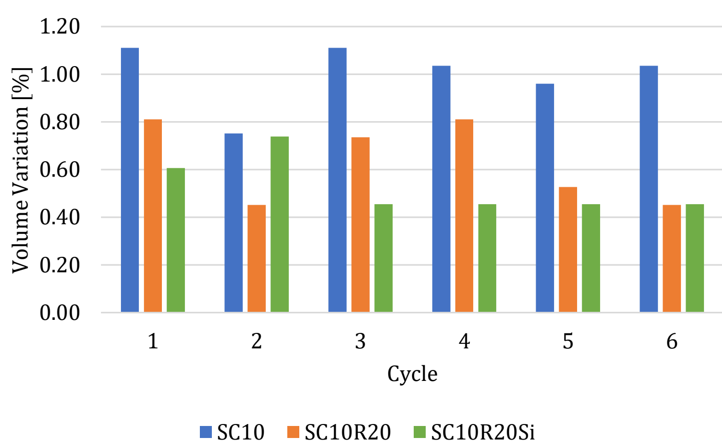


Figure 5.2: Volume Variations.

As for mass loss, the lowest value was of the $SC_{10}R_{20}$ composition, with a mean slightly lower than 9%. Figure 5.3 shows the mass loss means of the two specimens of each composition.

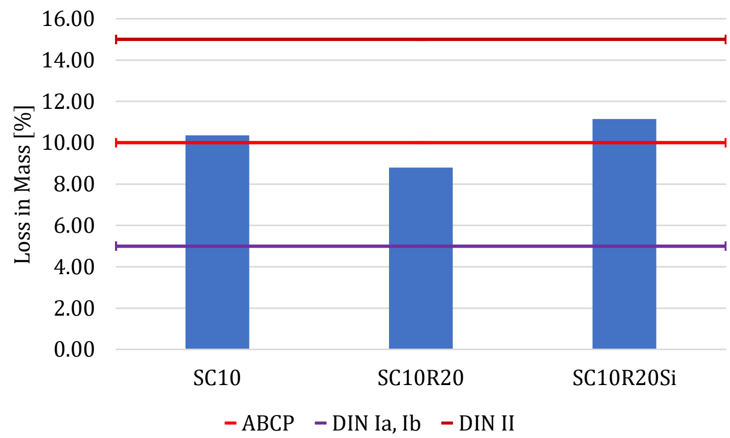


Figure 5.3: Loss in Mass.

Table 5.3 presents a summary of the results obtained, where for volume variation the average of the six cycles was considered.

Table 5.3: Volume Variation and Mass Loss After Cycles.

Composition	Volume Variation	Mass Loss	Unit
SC_{10}	1.00	10.35	%
$SC_{10}R_{20}$	0.63	8.80	%
$SC_{10}R_{20}Si$	0.53	11.15	%

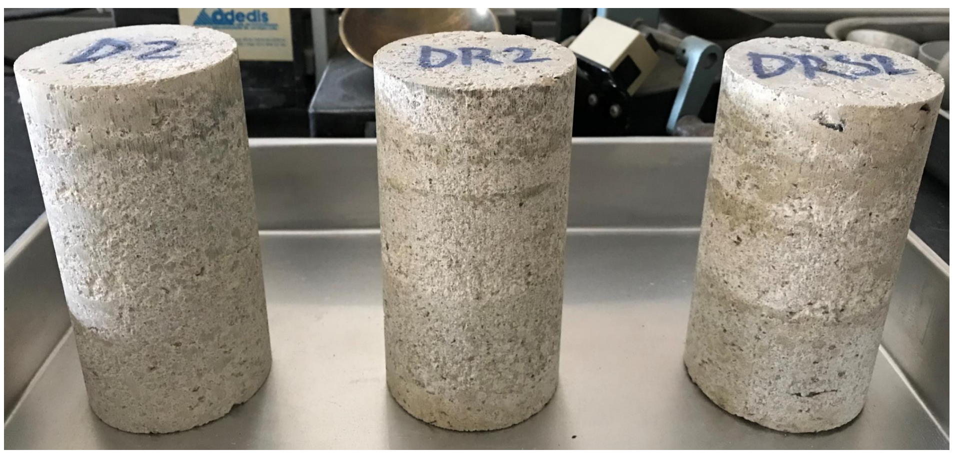
Visually the specimens did not undergo too many variations. Figure 5.4 shows the visual comparisons before the beginning of the cycles and at the end of the last step. Presenting from the left the compositions SC_{10}, $SC_{10}R_{20}$ and $SC_{10}R_{20}Si$.

When comparing the results with the standard used, it can be seen that according to the Brazilian limits, see Table 2.4, only the composition $SC_{10}R_{20}$ meets the requirement, being the one farthest from the limit the composition with silica fume.

In relation to German Standard all specimens comply with the limits shown in Table 2.11, considering that the blocks will be used in internal walls or protected external masonry. If they are of upper classes no composition meets the specified.

For Spanish Standard the checks for the wetting and drying cycles are through visual analysis. None of the irregularities that were exposed in Table 2.7 were observed, so that all specimens meet this standard.

(a) Before Cycles



(b) After Cycles

Figure 5.4: Visual Analysis.

The main cause of the mass loss in the wetting and drying test is brushing, which causes abrasion stresses in the soil-cement. However, masonry walls are weakly required for this effort, and the brushing step is considered unnecessary [62], [78].

5.3 Compressive Strength

This section will present the results of compressive strength that are divided into four parts, being: reference, saturated, aged and at high temperatures.

The reference tests are those which have not undergone any kind of procedure prior to the test, i.e. only remained for the curing time in the humid chamber. Saturated tests are the same specimens used for water absorption tests. In the tests of compressive strength with aging the same specimens of the wetting and drying cycles were used. Finally, the specimens were tested at high temperatures.

5.3.1 Reference Tests

This subsection presents the simple compressive strength tests performed on the three compositions. The results are presented for the different curing ages, with evaluation of resistance evolution. The comparisons between compositions are shown by curing time and finally verified if the values obtained are in accordance with the standards presented in Chapter 2.

SC_{10}

The values of maximum compressive strength reached by the specimens at 7 days and its average are shown in Table 5.4.

Table 5.4: Compressive Strength [MPa] at 07 days - SC_{10}.

Specimen	Individual	Average
C1	6.43	
C2	6.52	6.52
C3	6.24	
C4	6.90	

For the 14 days of cure the results are shown in Table 5.5.

Table 5.5: Compressive Strength [MPa] at 14 days - SC_{10}.

Specimen	Individual	Average
C13	6.64	
C14	7.20	6.66
C15	6.14	

Results at 28 days can be verified in Table 5.6. The tests were performed on different dates, so the averages were divided into partial and total.

Table 5.6: Compressive Strength [MPa] at 28 days - SC_{10}.

Specimen	Individual	Average Partial	Average Total
C5	8.02		
C6	8.25	7.78	
C7	6.74		
C8	8.12		
C9	7.42		
C10	7.41	7.25	
C11	6.09		
C12	8.07		
F100-R1	8.25		
F100-R2	6.92	7.57	7.38
F100-R3	7.53		
F200-R1	7.10		
F200-R2	7.59	7.20	
F200-R3	6.91		
F400-R1	5.84		
F400-R2	5.88	6.01	
F400-R3	6.31		
F600-R1	8.81		
F600-R2	8.10	8.41	
F600-R3	8.31		

Even the specimens having always been made in the same way, being a fully manual process, it is possible to notice a variation of the partial averages presented in Table 5.6 from 6.01 to 8.41. Some climatic factors may have interfered with this variation, such as dry climate, which generates a faster evaporation of the water contained in the mixture.

The stress×deformation curves of all ages are shown in Figure 5.5. In which the average curve of each age is presented.

With the presented data it is verified that most of the resistance is reached in the first ages, being the increase from 7 to 28 days of 13.21%.

$SC_{10}R_{20}$

Table 5.7 shows the values of maximum compressive strength, as well as the average found for the $SC_{10}R_{20}$ composition at 7 days of cure. For 14 days curing, the obtained compression results can be seen in Table 5.8.

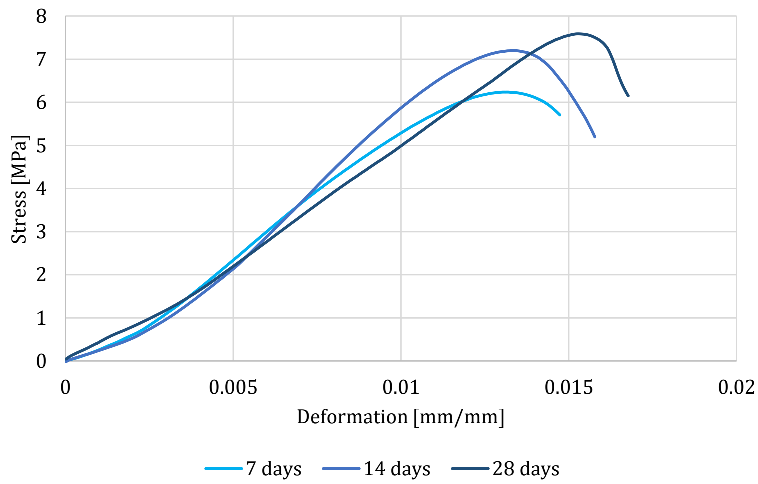


Figure 5.5: Stress×Deformation SC_{10}.

Table 5.7: Compressive Strength [MPa] at 07 days - $SC_{10}R_{20}$.

Specimen	Individual	Average
CR1	3.14	
CR2	3.49	3.74
CR3	3.84	
CR4	4.51	

Table 5.8: Compressive Strength [MPa] at 14 days - $SC_{10}R_{20}$.

Specimen	Individual	Average
CR9	3.06	
CR10	3.29	3.44
CR11	3.97	

For the last compression tests, 28 days of cure, the maximum values that the $SC_{10}R_{20}$ composition reached can be conferred in Table 5.9. These values were also divided into partial and total averages, considering the days of confection and test.

It can be seen in Table 5.9 three values that are far below the others, but which do not differ significantly among themselves. This variation of values, as well as that occurring in the results presented previously, can be explained by the low air humidity and high temperature that increases the evaporation of the water contained in the mixture.

To assess the evolution of the resistance increase, Figure 5.6 presents the average results for the three cure times.

Table 5.9: Compressive Strength [MPa] at 28 days - $SC_{10}R_{20}$.

Specimen	Individual	Average Partial	Average Total
CR5	5.47		
CR6	3.93	4.44	
CR7	4.91		
CR8	3.45		
FR100-R1	3.34		
FR100-R2	3.93	4.02	
FR100-R3	4.77		
FR200-R1	4.75		4.09
FR200-R2	5.15	4.86	
FR200-R3	4.67		
FR400-R1	2.12		
FR400-R2	2.33	2.31	
FR400-R3	2.49		
FR600-R1	4.59		
FR600-R2	5.20	4.73	
FR600-R3	4.40		

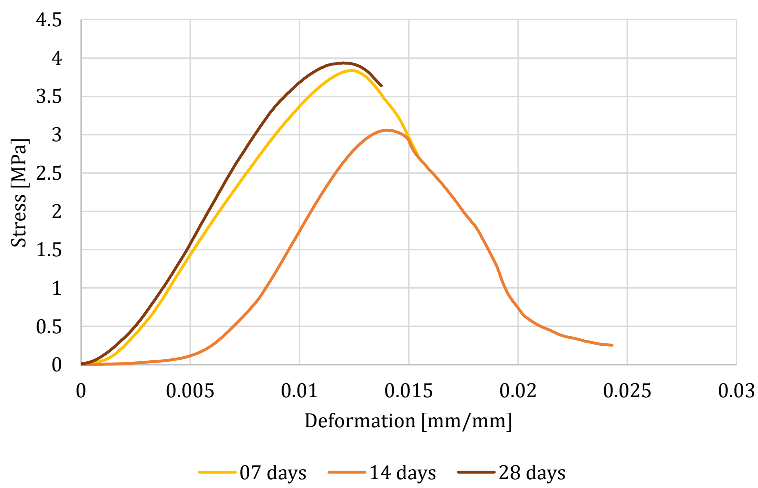


Figure 5.6: Stress×Deformation $SC_{10}R_{20}$.

There was, in this case, a decrease in compressive strength at the age of 14 days. Unexpected behavior that needs further study to better understand its reason. Resistance increase from 7 to 28 days was only 9.36%, that is, the highest percentage of resistance improvement occurred in the first 7 days of cure.

$SC_{10}R_{20}Si$

Tables 5.10 and 5.11 show the maximum strength values achieved by the $SC_{10}R_{20}Si$ composition at 7 and 28 days of age, respectively.

Table 5.10: Compressive Strength [MPa] at 07 days - $SC_{10}R_{20}Si$.

Specimen	Individual	Average
CSi1	2.98	
CSi2	3.12	3.26
CSi3	3.62	
CSi4	3.32	

Table 5.11: Compressive Strength [MPa] at 28 days - $SC_{10}R_{20}Si$.

Specimen	Individual	Average Partial	Average Total
CSi5	4.61		
CSi6	3.53	4.03	
CSi7	4.29		
CSi8	3.69		
FSi100-R1	2.80		
FSi100-R2	2.92	2.79	
FSi100-R3	2.65		
FSi200-R1	3.91		3.69
FSi200-R2	4.52	4.21	
FSi200-R3	4.19		
FSi400-R1	2.87		
FSi400-R2	2.17	2.62	
FSi400-R3	2.82		
FSi600-R1	4.64		
FSi600-R2	5.01	4.68	
FSi600-R3	4.38		

The resistance increase between the analyzed ages is 13.16%. The mean values can be seen in Figure 5.7, maintaining the pattern of higher resistance improvement in the early curing ages. The two curves present similar behavior.

Table 5.11, as in previous cases, shows two mean values below the others. That fact, as already said, may have been caused by the weather. In addition, these specimens were made on the same day, that is, they all have the same climatic factor.

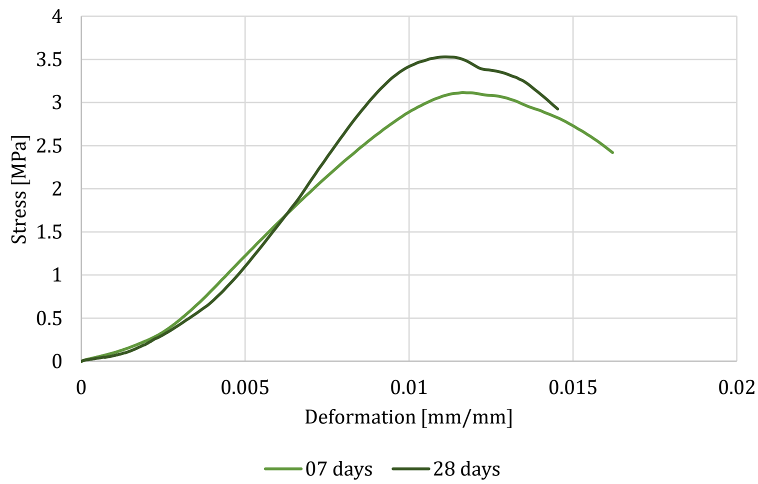


Figure 5.7: Stress×Deformation $SC_{10}R_{20}Si$.

Comparison of Results

Table 5.12 summarizes all the averages obtained in the compressive strength tests that were presented individually above.

Table 5.12: Summary of Compressive Strength.

Composition	07 days	14 days	28 days	Unit
Soil		0.88		MPa
SC_{10}	6.52	6.66	7.38	MPa
$SC_{10}R_{20}$	3.74	3.44	4.09	MPa
$SC_{10}R_{20}Si$	3.26	-	3.69	MPa

The compressive strength of SC_{10} is 1.80 times higher than $SC_{10}R_{20}$, and 2.00 times higher than $SC_{10}R_{20}Si$, at 28 days of cure. Even with such large differences, the lowest value still meets the most stringent standards used, as shown in Figure 5.8.

The lowest value obtained of 3.26 MPa according to the Spanish standard is classified as CEB 2, and class of strength 2 of the German standard. And the highest value can be classified as CEB 3 according to UNE and class of strength 5 according to DIN.

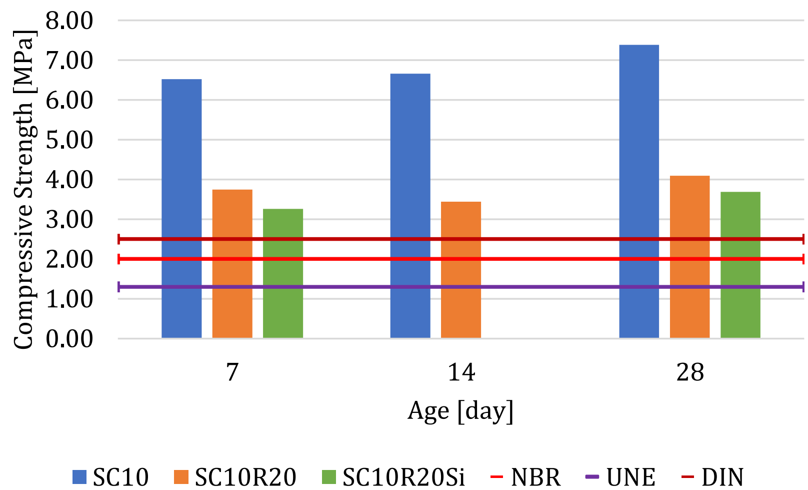
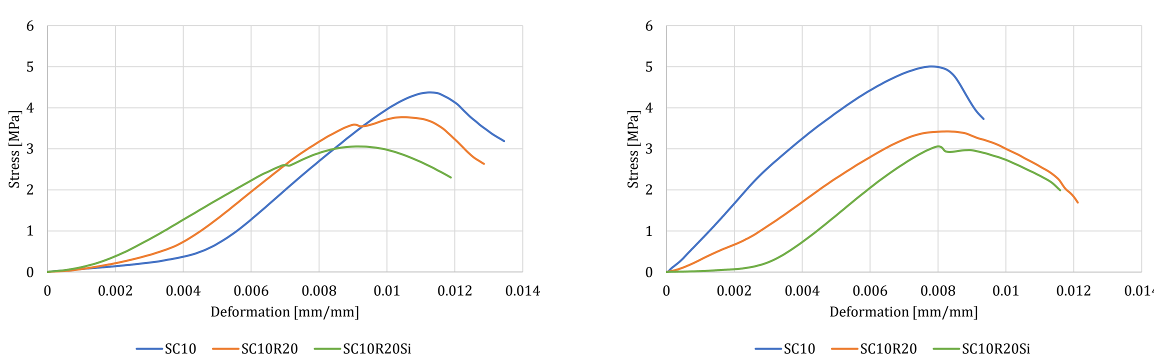


Figure 5.8: Compressive Strength Average.

5.3.2 Saturated

This subsection aims to present the compressive strength results of the cylindrical soil-cement specimens in the saturated condition, namely T1 and T2, and to compare those values with the reference values presented in the previous subsection. In addition to verifying if the saturated specimens still meet the standards.

Figure 5.9a shows the average stress×Deformation curves of the T1 specimens, beside the Figure 5.9b, which shows the same curves for T2 condition.



(a) Stress×deformation T1 (b) Stress×Deformation T2

Figure 5.9: Compressive Stress in Saturated Condition.

The maximum compressive strength averages were made for the three specimens of each condition. Table 5.13 presents these averages and the reference values.

Table 5.13: Compressive Strength in the Saturated Condition.

Composition	Reference	T1	T2	Unit
SC_{10}	7.38	4.57	4.82	MPa
$SC_{10}R_{20}$	4.09	3.58	3.49	MPa
$SC_{10}R_{20}Si$	3.69	3.07	3.13	MPa

The compressive strength averages are presented in Figure 5.10 as well as the values of reference and it's possible a direct comparison of the means.

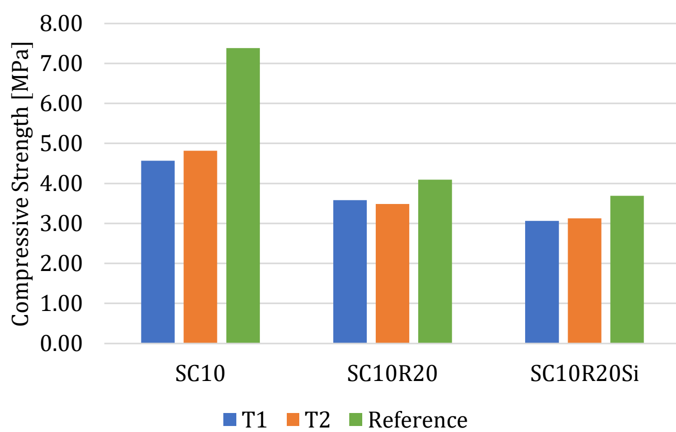


Figure 5.10: Comparison of Saturated and Reference Strengths.

With the exception of the $SC_{10}R_{20}$ composition, there was a small increase in resistance of T2 condition.

The SC_{10} composition was the most affected by the saturated condition, with the reference value being 1.53 times higher than saturated resistance value. The lowest value obtained in this analysis was in the $SC_{10}R_{20}Si$ composition, with 3.07 MPa in the T1 condition. Although this is a low value, it is still above all standards used for comparison.

5.3.3 Aged

The maximum compressive stresses obtained by the specimens after the accelerated aging cycles are presented in this subsection. These values are compared to reference values and guiding requirements. Furthermore, the effect of the cycles on the compressive strength of the specimens is also evaluated.

Tables 5.14, 5.15 and 5.16 present the individual and average results of the compressive strength for the three compositions studied.

Table 5.14: Compressive Strength After Cycles - SC_{10}.

Specimen	Individual	Average	Unit
D1	12.86		MPa
D2	11.56	12.27	MPa
D3	12.40		MPa

Table 5.15: Compressive Strength After Cycles - $SC_{10}R_{20}$.

Specimen	Individual	Average	Unit
DR1	7.14		MPa
DR2	5.31	6.03	MPa
DR3	5.65		MPa

Table 5.16: Compressive Strength After Cycles - $SC_{10}R_{20}Si$.

Specimen	Individual	Average	Unit
DSi1	5.46		MPa
DSi2	5.31	5.59	MPa
DSi3	5.99		MPa

Figure 5.11 shows the mean compressive strength after the six cycles and the reference values of all the compositions.

With the wetting and drying cycles the specimens increased compressive strength. For compositions SC_{10}, $SC_{10}R_{20}$ and $SC_{10}R_{20}Si$ the compressive strengths are higher at 1.66,

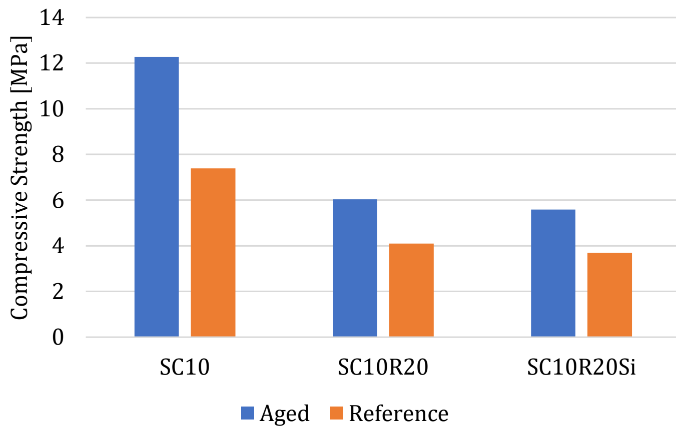


Figure 5.11: Comparison of Aged and Reference Strengths.

1.47 e 1.52, respectively. The heating generated during the drying of the specimens can be the cause of the increase of resistance, since this was a fact also noticed when the specimens heated for the tests of compressive strength at high temperature. For complete evaluation, further studies should be done with experimental research.

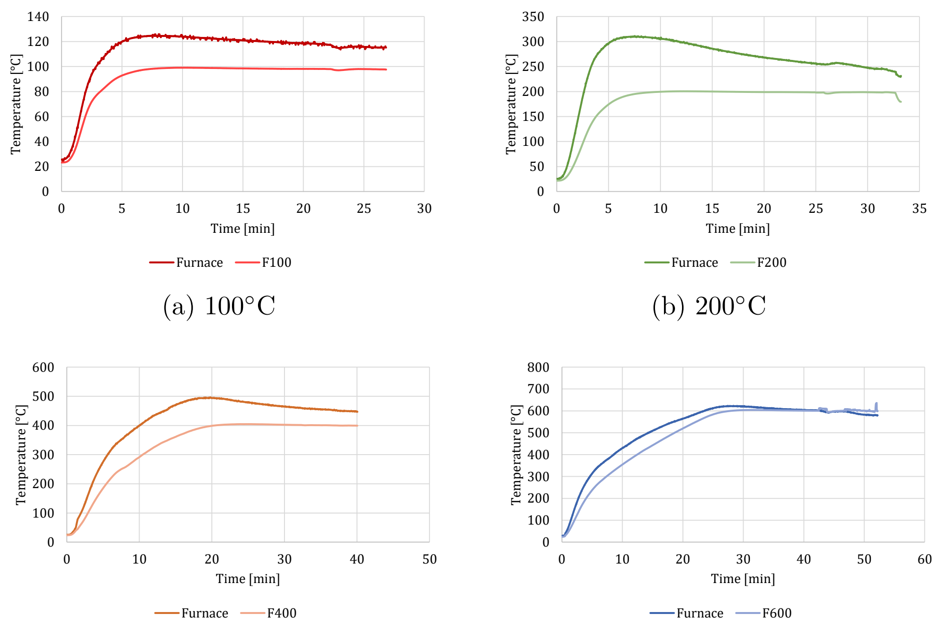
As for the standards used, as there was an increase in resistance, the composition with the lowest average can be classified in the highest class of strength of the UNE (CEB 3), and in the class of strength 4 of the DIN.

5.3.4 Compressive Strength at High Temperature

This subsection presents the experimental results of compressive strength at high temperatures. First the average heating curves of the specimens are presented, followed by the compressive strengths of each composition at all temperatures. Finally, the results are presented in each temperature range. The compressive strengths are compared only with the specimens that were made on the same days, and which were presented previously as F-R (Fire-Reference), for each temperature.

Heating Curve

All specimens presented a similar behavior when subjected to the same heating. Figure 5.12 shows the heating of the composition SC_{10} at the four temperature readings (100°C, 200°C, 400°C and 600°C).



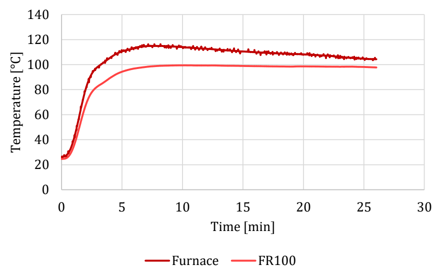
(a) 100°C (b) 200°C

(c) 400°C (d) 600°C

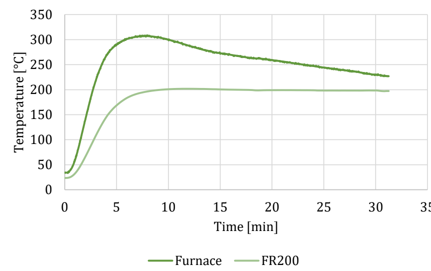
Figure 5.12: Heating Curve SC_{10}.

For 600°C, at the end of the test, the temperature of the specimen exceeds the temperature of the oven. This behavior has to do with the fact that the thermocouple that measures the oven temperature comes into contact with the specimen, causing a small measurement error.

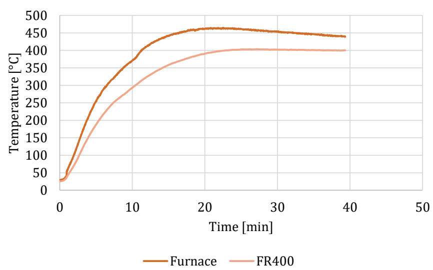
From Figures 5.13 and 5.14 it can be seen the temperatures recorded by the thermocouples placed in the specimen and the thermocouple designated by "furnace" recorded the temperatures of the air inside the furnace, for the $SC_{10}R_{20}$ and $SC_{10}R_{20}Si$ composition, respectively. The temperatures of the specimens are always below the furnace temperature.



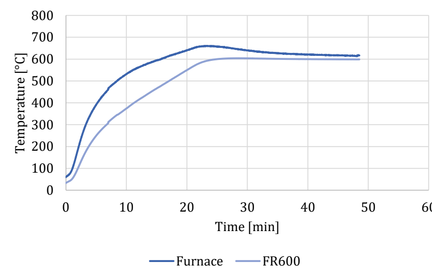
(a) 100°C



(b) 200°C

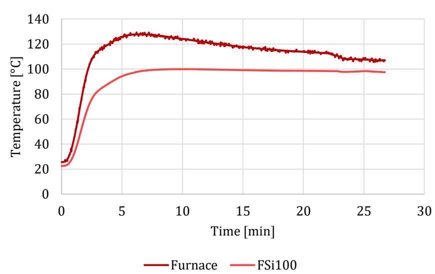


(c) 400°C

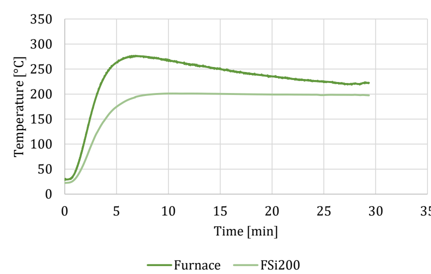


(d) 600°C

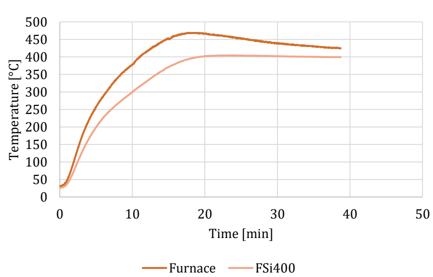
Figure 5.13: Heating Curve $SC_{10}R_{20}$.



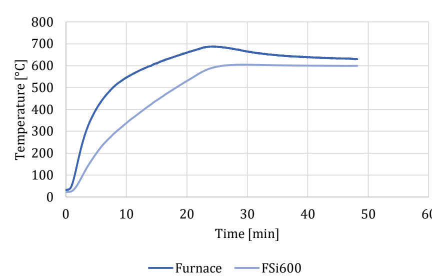
(a) 100°C



(b) 200°C



(c) 400°C



(d) 600°C

Figure 5.14: Heating Curve $SC_{10}R_{20}Si$.

Results by Composition

The results obtained in each of the three compositions studied under the effect of the above mentioned temperatures, and comparisons with their respective references, are presented herein.

Figure 5.15 shows the compressive strengths of the SC_{10} specimens for the four temperatures together with the reference specimens made for each temperature. The same values are also shown in Table 5.17.

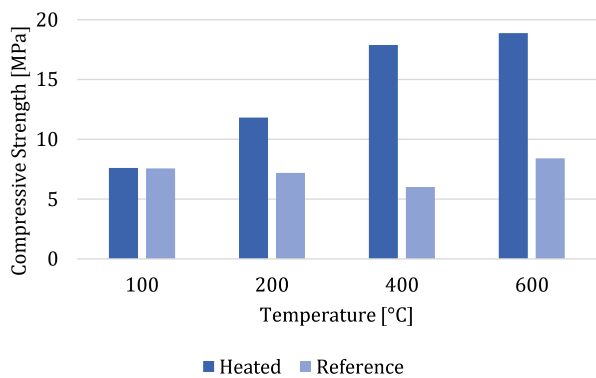


Figure 5.15: Comparison of Heated and Reference Strengths - SC_{10}.

Table 5.17: Compressive Strength at High Temperature - SC_{10}.

	100°C	200°C	400°C	600°C	Unit
Heated	7.60	11.82	17.89	18.88	MPa
Reference	7.57	7.20	6.01	8.41	MPa

Although the temperature of 600°C showed the highest compressive strength, the temperature that obtained the highest gain was 400°C, with 197.64% in relation to the reference specimen.

For $SC_{10}R_{20}$ specimens, the values of the compressive strength with heating and reference are shown in Figure 5.16 and Table 5.18.

As in the previous one the higher compressive strength was reached in 600°C, but also in the same way, the greater gain occurred in the temperature of 400°C, being this 2.71 times the reference value. In this case it was also noted that when heated at 100°C the resistance was lower than the reference value.

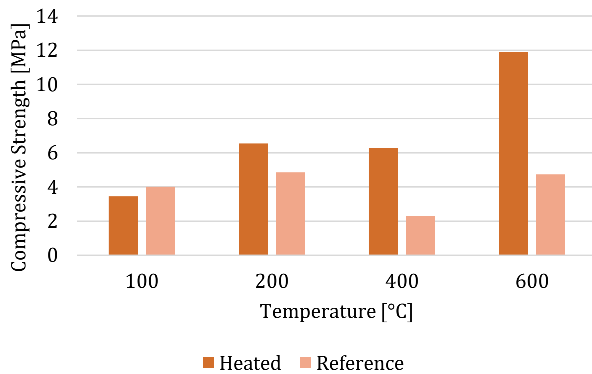


Figure 5.16: Comparison of Heated and Reference Strengths - $SC_{10}R_{20}$.

Table 5.18: Compressive Strength at High Temperature - $SC_{10}R_{20}$.

	100°C	200°C	400°C	600°C	Unit
Heated	3.45	5.64	6.28	11.90	MPa
Reference	4.02	4.86	2.31	4.73	MPa

The final composition evaluated was $SC_{10}R_{20}Si$. Its compressive strength values can be seen in Table 5.19, and graphically in Figure 5.17.

Table 5.19: Compressive Strength at High Temperature - $SC_{10}R_{20}Si$.

	100°C	200°C	400°C	600°C	Unit
Heated	2.82	6.33	7.74	9.43	MPa
Reference	2.79	4.21	2.62	4.68	MPa

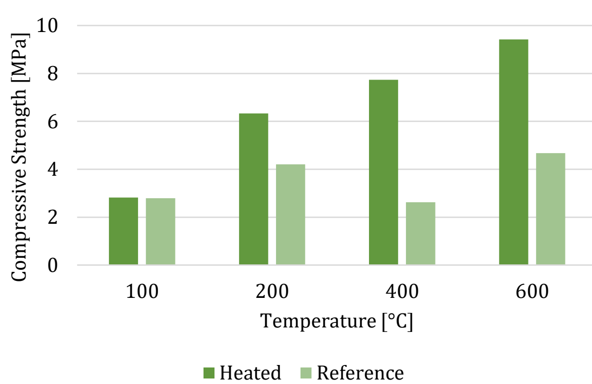


Figure 5.17: Comparison of Heated and Reference Strengths - $SC_{10}R_{20}Si$.

Following the same behavior of the other compositions, $SC_{10}R_{20}Si$ also obtained the highest value of compressive strength at 600°C and the highest increase from reference at 400°C, with 2.95 times.

Since all compositions showed higher gains at 400°C, further research and experiments should be performed to determine the exact temperature at which the highest gain is obtained. These gains can also provide greater incorporation of waste, which means greater utilization. Furthermore, from 200°C it is already possible to note the increases in the compressive strengths.

Results by Temperature.

In this subsection are presented the mean compressive strength by temperature. Thus, the direct comparison of the values of the three compositions at each temperature is possible.

Figure 5.18 shows the stress×Deformation curve for the three compositions (F100, FR100 and FSi100) at 100°C. This curve represents the average of the three specimens made in each test for each composition.

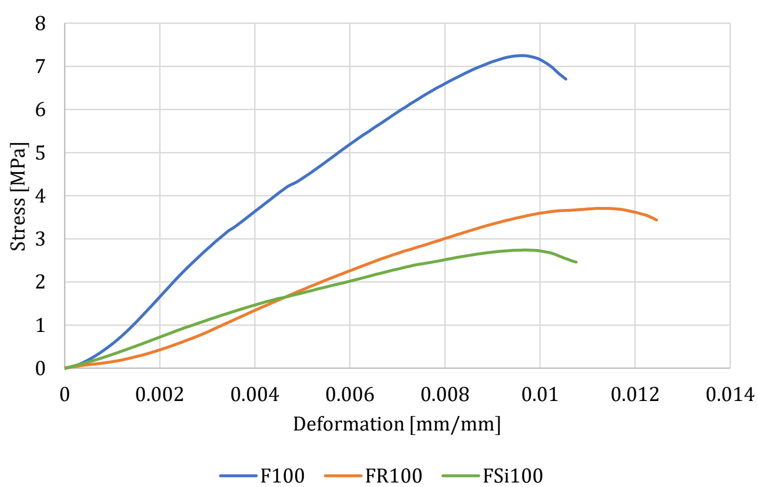


Figure 5.18: Stress×Deformation at 100°C.

The behavior of the two mixtures with residues shows to be similar, whereas the composition without residue besides reaching a much higher compressive stress, has behavior different from the others.

At 200°C a more similar behavior is observed between the three curves, as shown in

Figure 5.19. In addition, at that level the two waste compositions have close compressive strength values.

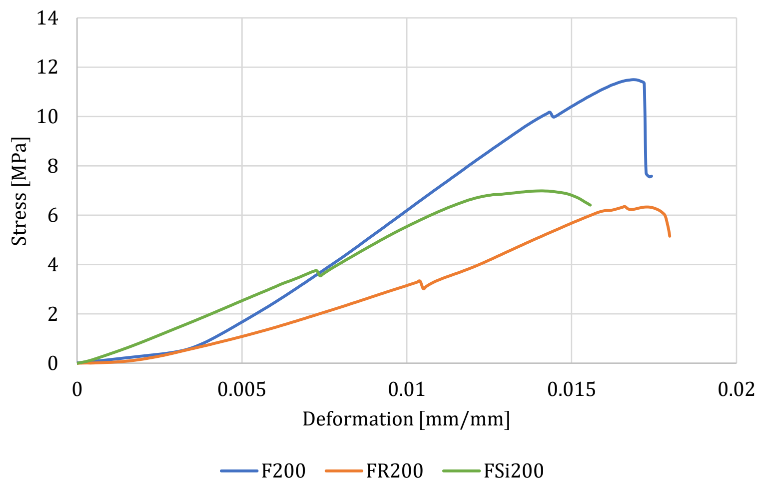


Figure 5.19: Stress×Deformation at 200°C.

Increasing the temperature, it was verified a greater increase of the compressive strengths. At 400°C Figure 5.20 shows that the soil-cement mixture achieves a compressive stress of almost 18 MPa.

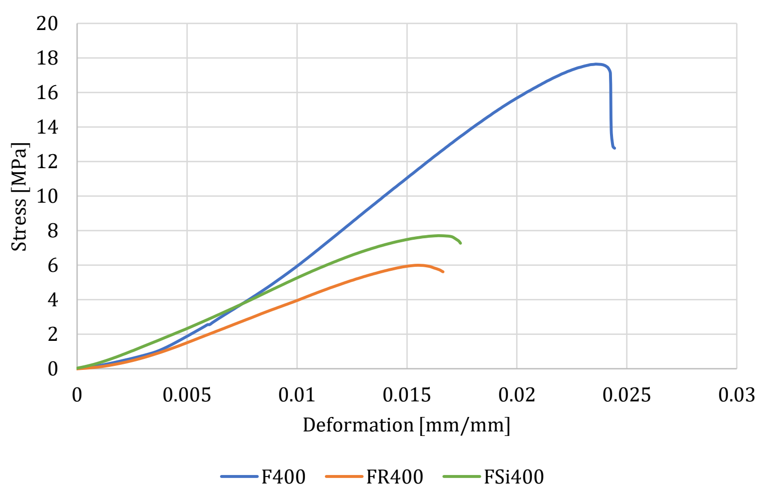


Figure 5.20: Stress×Deformation at 400°C.

Unlike the other temperatures, at 400°C the silica composition outperforms the composition without silica.

Finally, the stress×Deformation curves at 600°C are shown in Figure 5.21. Where again the mean curve of the $SC_{10}R_{20}$ specimens exceeds those of $SC_{10}R_{20}Si$.

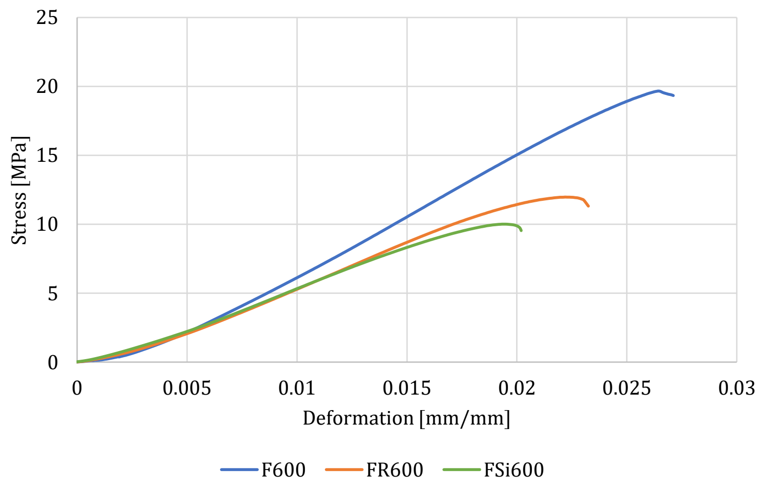


Figure 5.21: Stress×Deformation at 600°C.

When evaluating Figure 5.21, it is noted that the lower compressive strength is close to 10 MPa, 2.50 times higher than the minimum required by DIN. This temperature has the highest values, reaching 18.88 MPa in the SC_{10} composition.

Table 5.20 summarizes the general averages obtained in the tests. Also shown in Figure 5.22, where it is possible to observe the increase of compressive strength with the increase in temperature.

Table 5.20: Compressive Strength by Temperature.

Composition	20°C	100°C	200°C	400°C	600°C	Unit
SC_{10}	7.30	7.60	11.82	17.89	18.88	MPa
$SC_{10}R_{20}$	3.98	3.45	6.54	6.28	11.90	MPa
$SC_{10}R_{20}Si$	3.57	2.82	6.33	7.74	9.43	MPa

At the end of the experiments it was observed that no matter what the temperature, the composition without residues always has the greatest compressive strengths, as expected.

Excluding the temperature of 400°C, compositions with SF addition always have the smallest strengths.

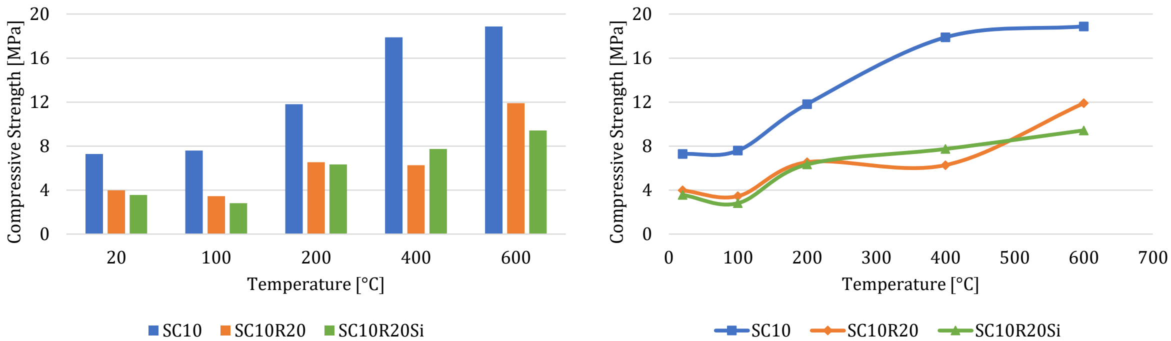


Figure 5.22: Evolution of Compressive Strength with Temperature Increase.

When the temperature is increased to 100°C the compressive strengths are very close to or less than those of reference. And at 600°C he highest resistances are reached.

It was noticed that the exhaled smell of the specimens when heated to 200°C was increased, but when the temperature reached 400°C the smell were no longer perceived. Therefore, this temperature increase should be investigated and tested for odor elimination treatment caused by the organic compound.

Chapter 6

Conclusion and Future Work

6.1 Developed Works

Cylindrical specimens of soil-cement with addition of municipal organic residues were constructed reducing the disposal of these residues and performing better use. Standards from three countries were used, namely from Brazil, Spain and Germany, to characterize the specimens. The compositions studied were compared to each other using the without residue mixture as reference, and compared to the standards cited above. It was proposed the use of silica fume in order to improve the characteristics of the specimens with residue, but this solution was not efficient, being always less to the other compositions. All three compositions fulfill the requirement of water absorption by immersion with slack. For durability, the specimens only meet the mass loss of the German standard, if they are used in moisture protected masonry, and have values very close to the Brazilian limits. In the compressive strength tests all the compositions satisfy the three standards, it was noticed that the air humidity in the day of the confection interferes in the results, being that the compositions that were made in drier days obtained the worse results. High temperature compressive strength test was performed on the specimens, all specimens as of 200°C increased the compressive strength, reaching almost 200%.

6.2 Future Works

This work can be continued through experimental research which is described below:

- Carry out further studies to eliminate odors exhaled by organic waste.
- Vary the percentages of waste and cement to optimize the use of waste and cement.
- Manufacture blocks in controlled temperature and humidity environments to verify the actual interference of these factors.
- Carry out wetting and drying tests without the brushing step to compare the mass losses.
- Carry out compressive strength tests at other curing ages to verify the interference of the organic compound in the cement hydration over time.
- Build walls with the ecological blocks to establish a resistance relationship between the blocks and the walls.

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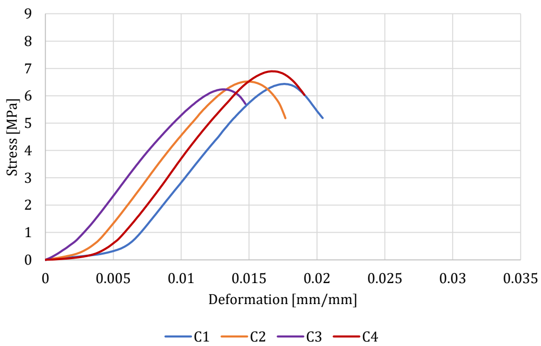
Appendix A

Stress$\times$Deformation Curves



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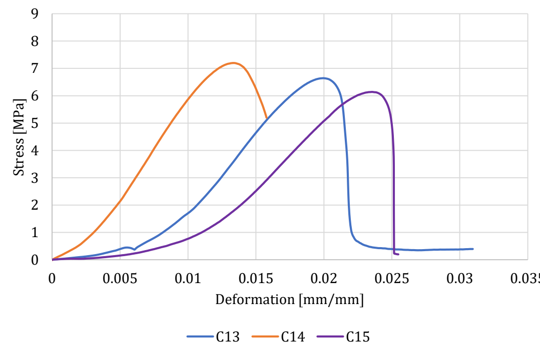

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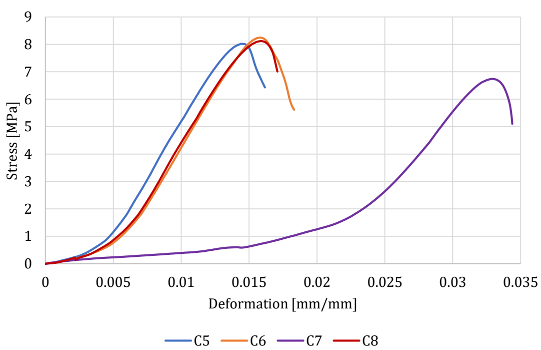
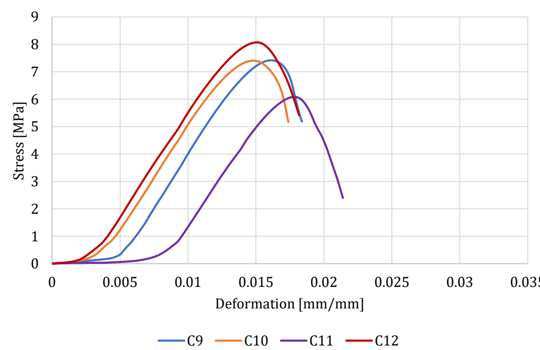


(c) 28 days



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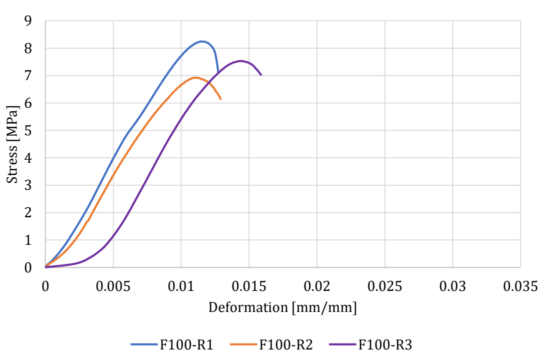
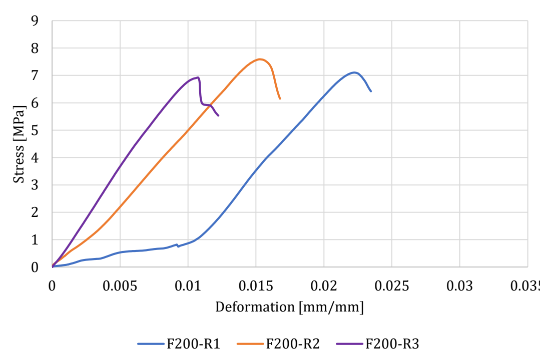
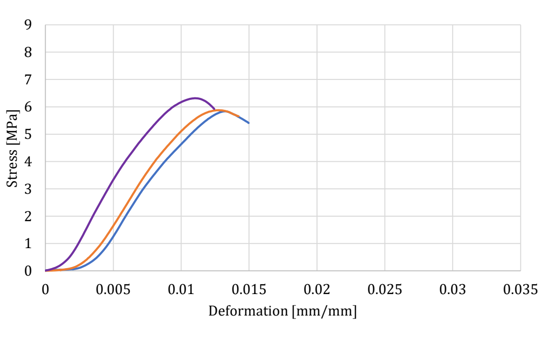


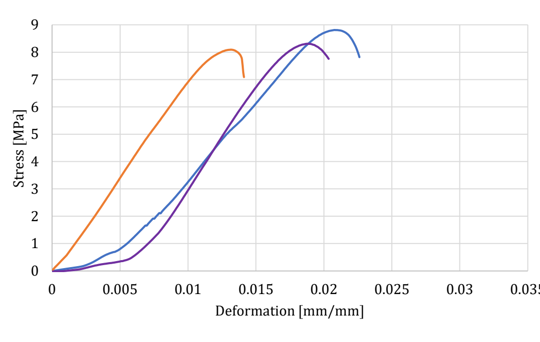
(e) 28 days



(f) 28 days

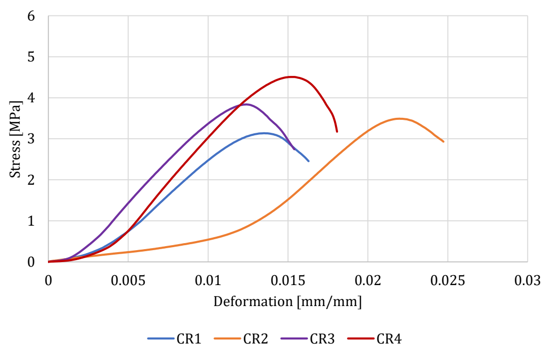


(g) 28 days

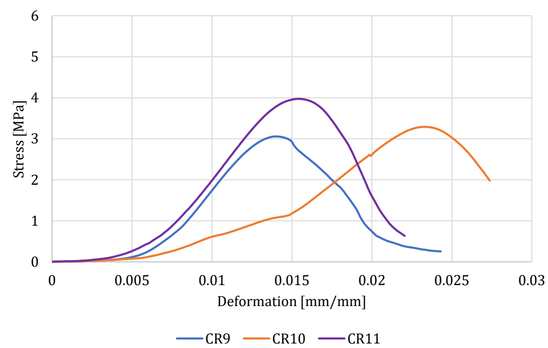


(h) 28 days

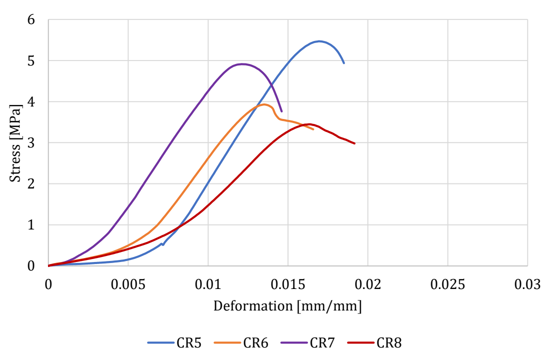
Figure A.1: Standard Compressive Stress SC_{10}.



(a) 7 days



(b) 14 days



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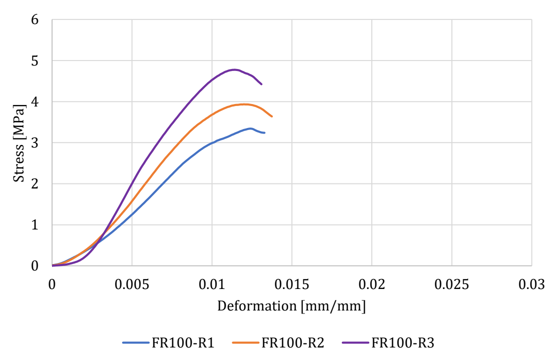

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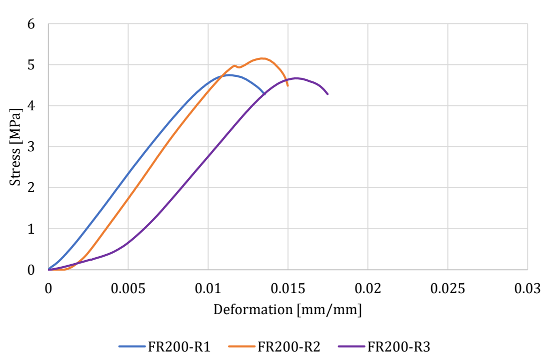

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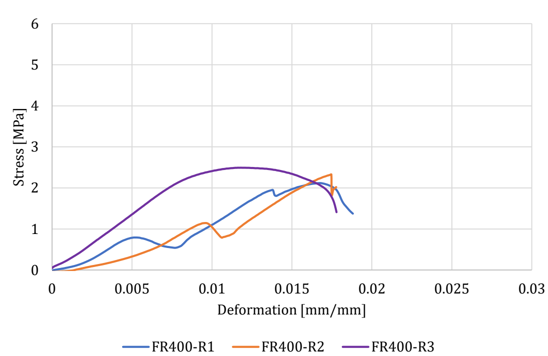

(f) 28 days

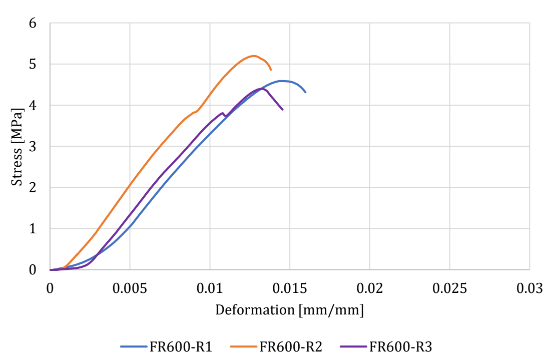

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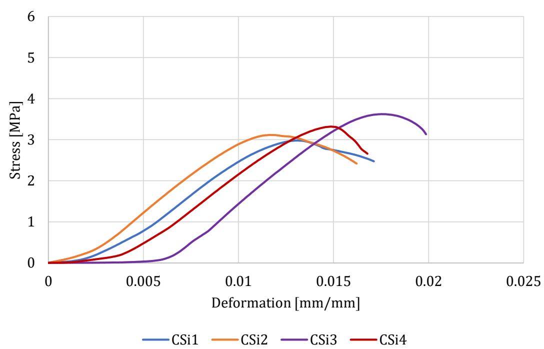
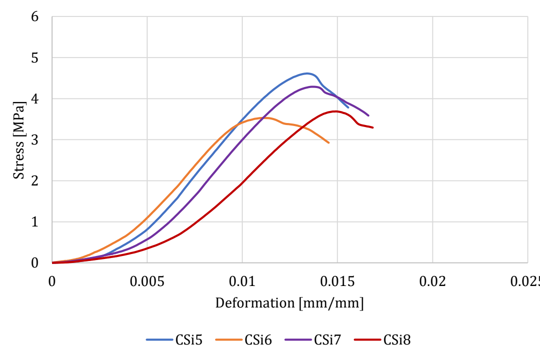
Figure A.2: Standard Compressive Stress $SC_{10}R_{20}$.



(a) 7 days



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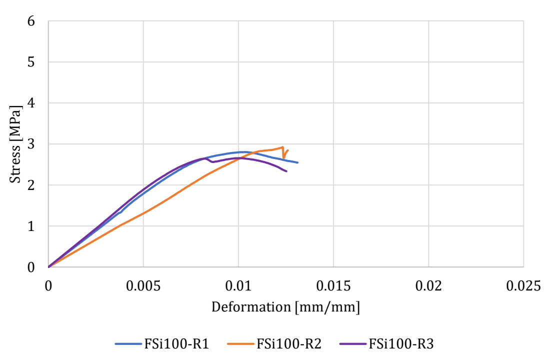
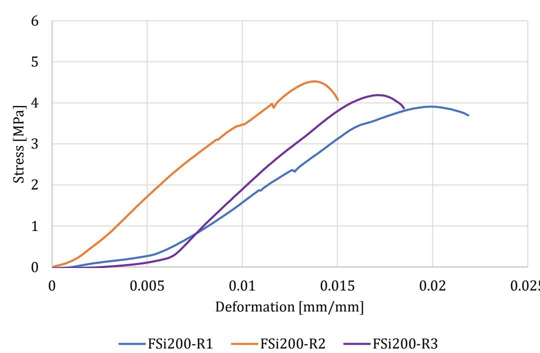
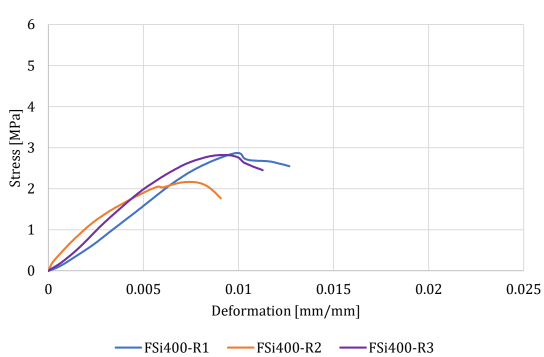


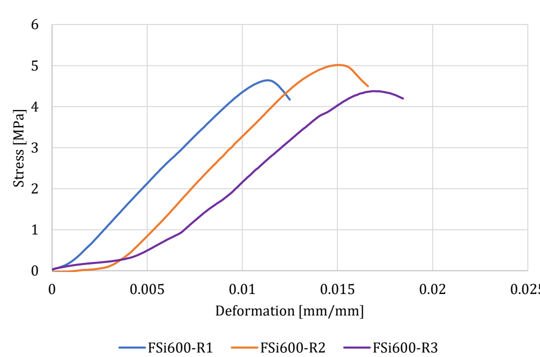
(c) 28 days



(d) 28 days



(e) 28 days



(f) 28 days

Figure A.3: Standard Compressive Stress $SC_{10}R_{20}Si$.

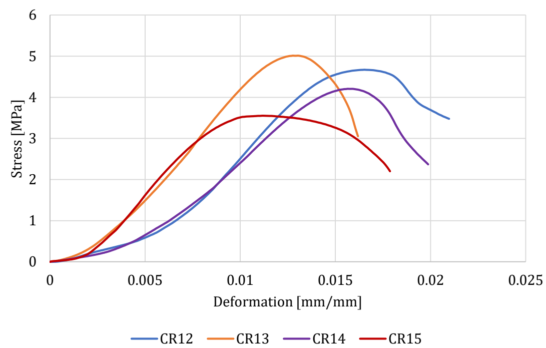


Figure A.4: Standard Compressive Stress with 10% Residue - $SC_{10}R_{10}$.

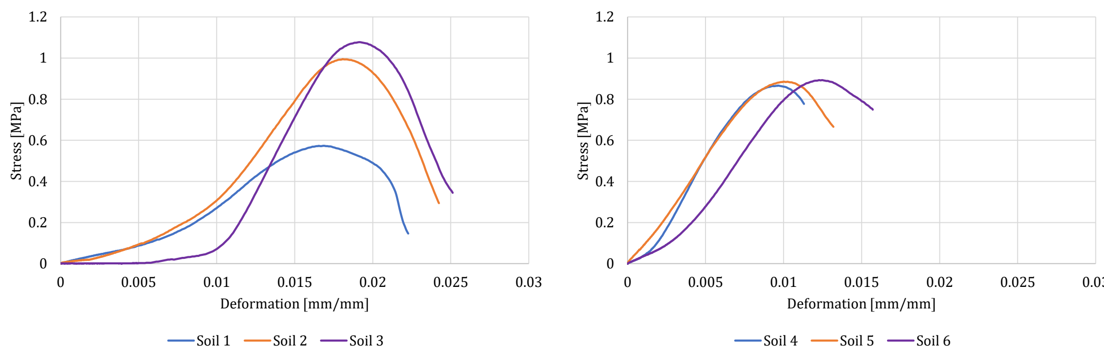
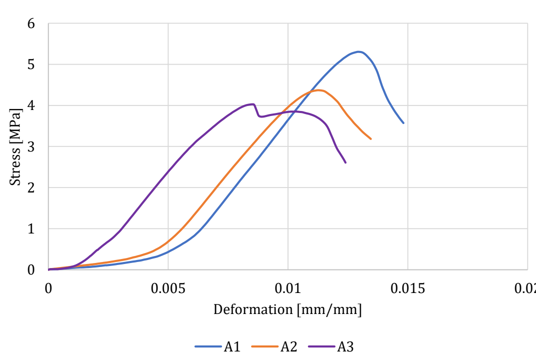
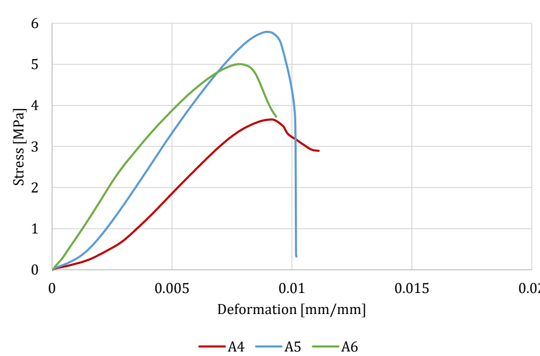


Figure A.5: Standard Compressive Stress Soil.

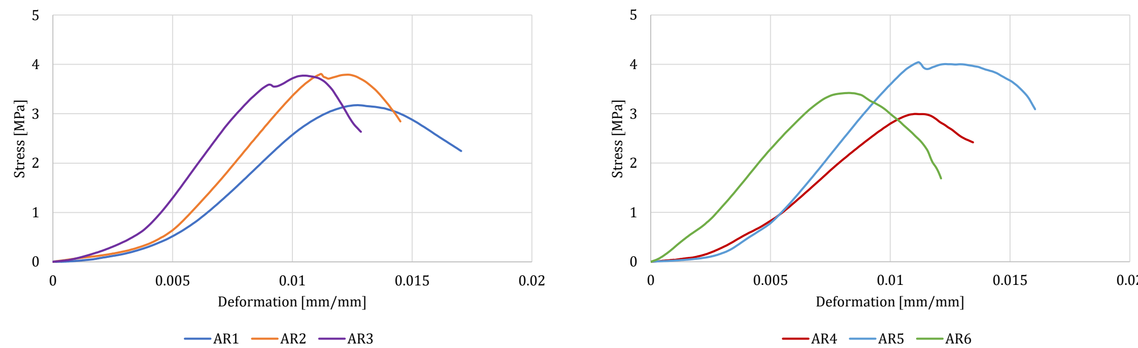


(a) T1



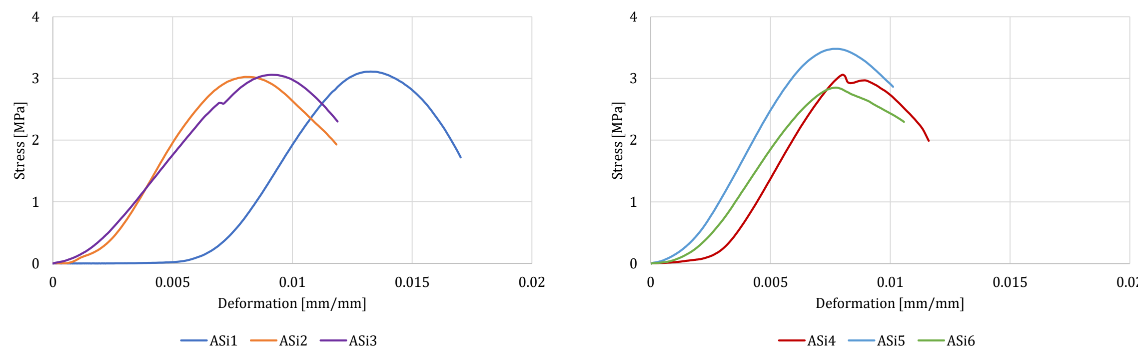
(b) T2

Figure A.6: Saturated Compressive Stress SC_{10}.



(a) T1 (b) T2

Figure A.7: Saturated Compressive Stress $SC_{10}R_{20}$.



(a) T1 (b) T2

Figure A.8: Saturated Compressive Stress $SC_{10}R_{20}Si$.

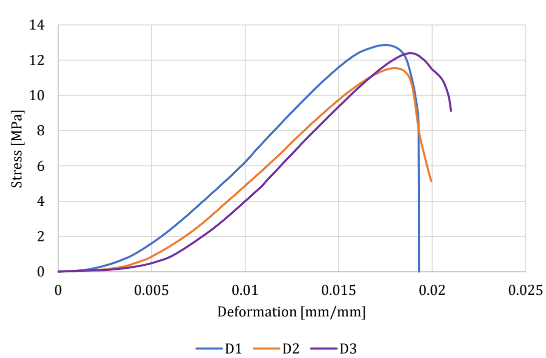


Figure A.9: Aged Compressive Stress SC_{10}.

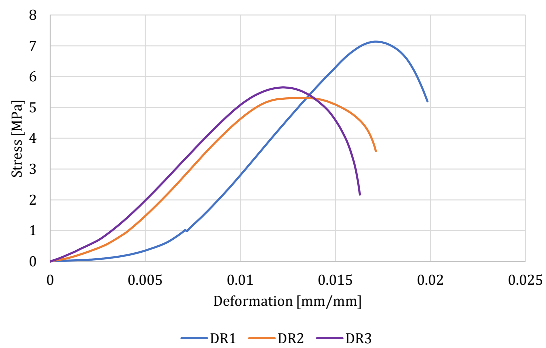


Figure A.10: Aged Compressive Stress $SC_{10}R_{20}$.

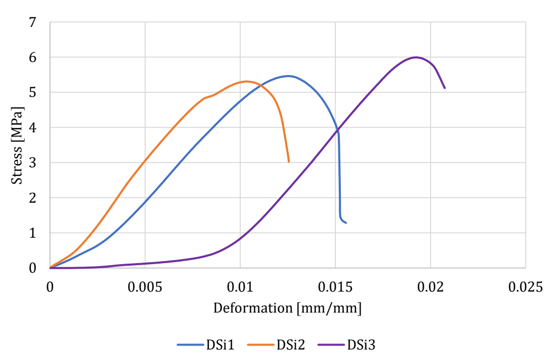
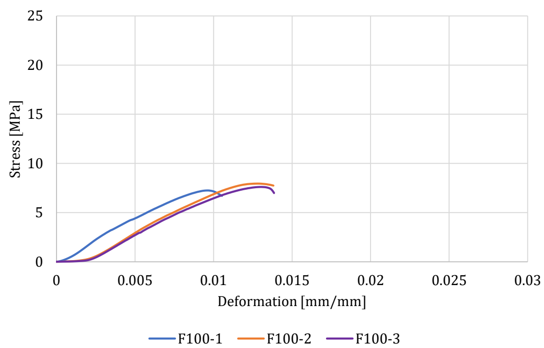
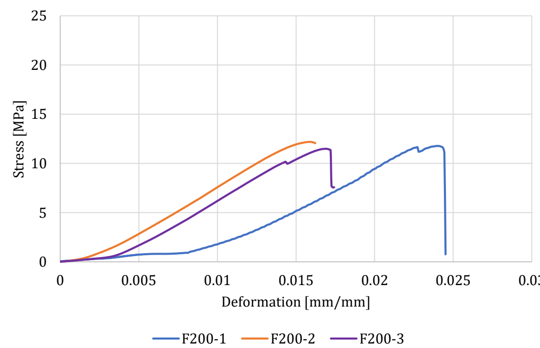


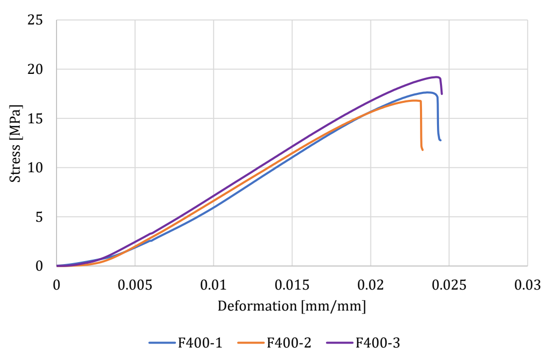
Figure A.11: Aged Compressive Stress $SC_{10}R_{20}Si$.



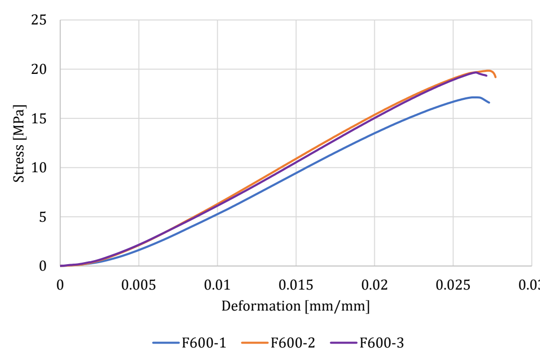
(a) 100°C



(b) 200°C

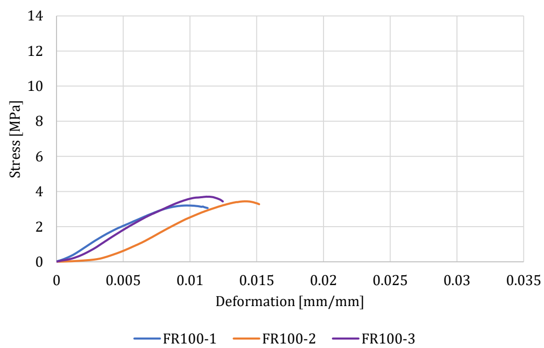


(c) 400°C

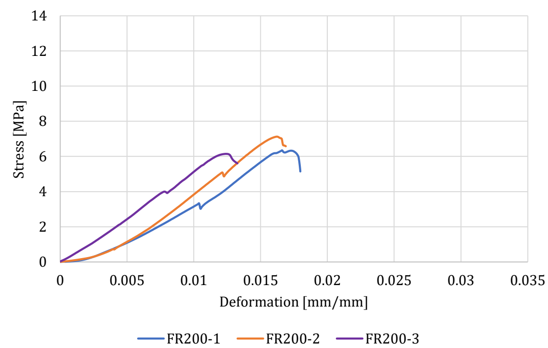


(d) 600°C

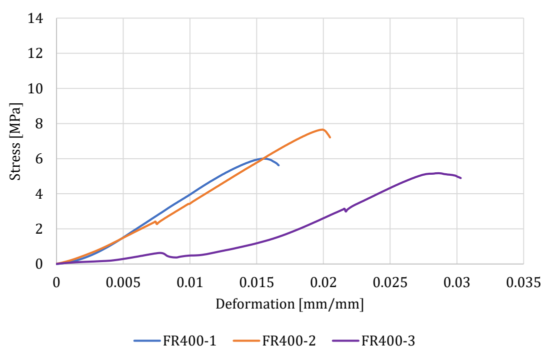
Figure A.12: Heated Compressive Stress SC_{10}.



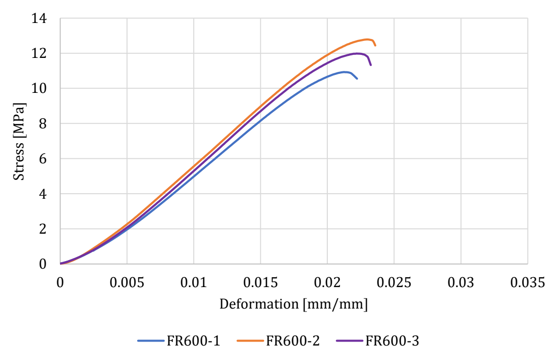
(a) 100°C



(b) 200°C

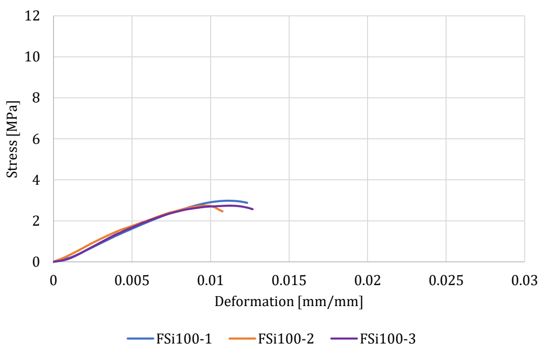


(c) 400°C

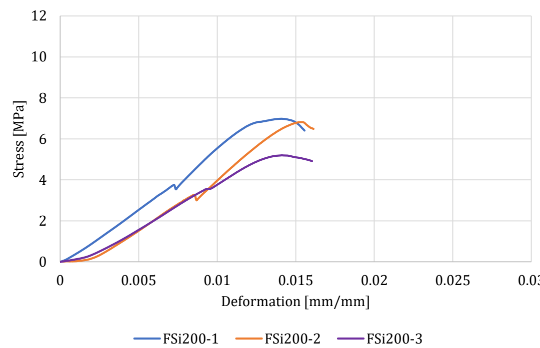


(d) 600°C

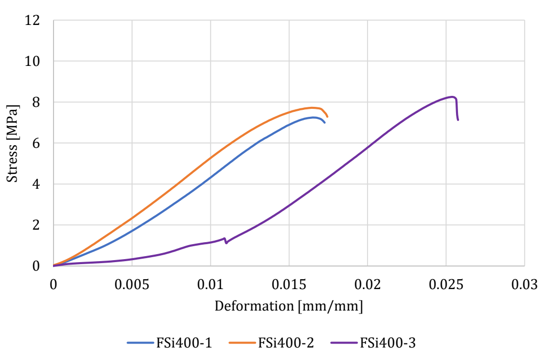
Figure A.13: Heated Compressive Stress $SC_{10}R_{20}$.



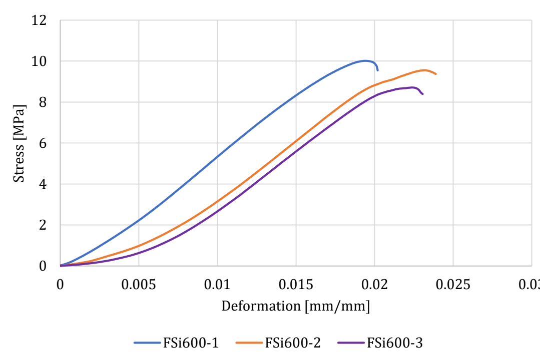
(a) 100°C



(b) 200°C



(c) 400°C



(d) 600°C

Figure A.14: Heated Compressive Stress $SC_{10}R_{20}Si$.