Revisiting vernacular technique:
Engineering a low environmental impact earth stabilisation method

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Abstract

The major drawbacks of earth as a construction material — such as its low water stability and moderate strength — have led mankind to stabilize earth. Different civilizations developed vernacular techniques mainly focussing on lime, pozzolan or gypsum stabilization. Recently, cement has become the most commonly used additive in earth stabilization as it improves the strength and durability of plain earth. Also, it is a familiar and globally available construction material. However, using cement as an additive reduces the environmental advantages of earth and run counter to global targets regarding the reduction of CO_2 emissions. Alternatives to cement stabilization are currently neither efficient enough to reduce its environmental impact nor allow the possibility of obtaining better results than those of cement. As such, this thesis deals with the rediscovery of a reverse engineering approach for a low environmental impact earth stabilization technique, aiming to replace cement in earth stabilization.

The first step in the method consists in a comprehensive review of earth stabilization with regards to earthen building standards and soil classification, which allows us to identify the research gap. The review showed that there is great potential in using other additives which result in similar improvements as those achieved by cement. However, the studies that have been conducted so far either use expansive soils, which are not suitable for earth constructions or artificial pozzolans that indirectly contribute to CO_2 emissions. This is the main research gap.

The key concept for the development in the second step of the method is to combine vernacular additives to both improve the strength and durability of plain earth and to reduce the CO_2 emissions. Various earth-mixtures were prepared and both development and performance tests were done to investigate the performance of this technique. The laboratory analyses on mix-design have proven a high durability and the results show a remarkable increase in strength performance. Furthermore, a significant reduction in CO_2 emissions in comparison to cement stabilization could be shown.

The third step of the method discusses the results drawn from the experimental programme. In addition, the potential of the new earth mixture with regards to its usability in the field of building construction and architectural design is further elaborated on.

The method used in this study is the first of its kind that allows investors to avoid the very time-consuming processes such as finding a suitable source for soil excavation and soil classification. The developed mixture has significant workability and suitability for production of stabilized earthen panels — the very first of its kind. Such a panel is practically feasible,

reasonable, and could be integrated into earthen building standards in general and in particular to DIN 18948, which is related to earthen boards and published in 2018.

Kurzfassung

Die wesentlichen Nachteile des Lehms als Baumaterial, wie geringe Wasserbeständigkeit und mäßige Festigkeit, haben die Menschheit veranlasst, den Lehm zu stabilisieren. Verschiedene Zivilisationen entwickelten vernakuläre Techniken, die sich hauptsächlich auf die Stabilisierung durch Kalk-, Puzzolan- oder Gipszugabe konzentrierten. In letzter Zeit ist Zement das am häufigsten verwendete Zusatzmittel bei der Lehmstabilisierung geworden, da es die Festigkeit und Haltbarkeit von Lehm verbessert. Es ist auch ein gewöhnliches und weltweit verfügbares Baumaterial. Die Verwendung von Zement als Zusatz verringert jedoch die ökologischen Vorteile des Lehms und widerspricht dem globalen Ziel der Reduzierung von CO_2-Emissionen. Alternativen zur Zementstabilisierung sind derzeit weder effizient genug, um die Umweltbelastung zu verringern, noch um bessere Ergebnisse als Zement zu erzielen. Daher befasst sich diese Arbeit mit der Wiederentdeckung eines sogenannten „Reverse-Engineering“ Ansatzes für die Lehmstabilisierungstechnik mit geringen Umweltauswirkungen, der auf den Ersatz von Zement bei der Lehmstabilisierung abzielt.

Der erste Schritt der Methode besteht in einer umfassenden Analyse der Lehmstabilisierung im Hinblick auf Lehmbaunormen und Bodenklassifizierung, anhand derer die Forschungslücke identifiziert wurde. Die Analyse ergab, dass die Verwendung alternativer Zusätze, die zu einer ähnlichen Verbesserung führen wie Zement, ein großes Potenzial hat. Die bisher durchgeführten Studien verwenden jedoch entweder expansive Böden, die nicht für Lehmbaukonstruktionen geeignet sind, oder künstliche Puzzolane, die indirekt zu den CO_2-Emissionen beitragen. Dies ist die Hauptforschungslücke.

Das Schlüsselkonzept für die Entwicklung der Methode im zweiten Schritt besteht darin, vernakuläre Zusatzstoffe zu kombinieren, um sowohl die Festigkeit und Durabilität des Lehms zu verbessern als auch die CO_2-Emissionen zu reduzieren. Es wurden verschiedene Lehmmischungen hergestellt und Prüfungen durchgeführt, um die Leistungsfähigkeit dieser Technik zu untersuchen. Die Laboranalysen der Lehmmischungen beweisen eine hohe Haltbarkeit und die Ergebnisse zeigen eine bemerkenswerte Steigerung der Festigkeit. Darüber hinaus konnte eine signifikante Reduzierung der CO_2-Emissionen im Vergleich zur Zementstabilisierung nachgewiesen werden.

Im dritten Schritt der Methode werden die Ergebnisse der durchgeführten Versuche erörtert. Darüber hinaus wird das Potenzial des neuen Lehmgemisches hinsichtlich seiner Verwendbarkeit im Bereich des Bauwesens und der architektonischen Gestaltung herausgearbeitet.

Die in dieser Studie verwendete Methode ist die erste ihrer Art, mit der Investoren zeitaufwändige Prozesse wie die Suche nach einer geeigneten Quelle für Lehmaushub und die Bodenklassifizierung vermeiden können. Die entwickelte neuartige Mischung weist eine sehr gute Verarbeitbarkeit und Eignung für die Herstellung von stabilisierten Lehmplatten auf. Ein solches Paneel ist praktisch umsetzbar und könnte in Lehmbaunormen im Allgemeinen und im Besonderen in die DIN 18948 integriert werden, die sich auf Lehmbauplatten bezieht und 2018 veröffentlicht wurde.

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Abbreviations

CA	Citric Acid
CASH	Calcium Alumino-Silicate Hydrates Calcium
CASHH	Calcium Aluminum Silicate Hydroxide Hydrate
CHS	Calcium Silicate Hydrates
CWA	Capillary Water Absorption
DEF	Delayed Ettringite Formation
FA	Fly Ash
FS	Flexural Strength
CS	Compressive Strength
ETGL	Earth+Trass+Gypsum+Lime
FTC	Freeze-Thaw Cycle
GL	Gypsum+Lime
GSD	Grain Size Distribution
CS	Compressive Strength
OPC	Ordinary Portland Cement
PE	Plain Earth
XRD	X-Ray Diffraction
XRF	X-Ray Fluorescence Spectrometry
SE	Stabilized Earth
SEP	Stabilized Earth Panel
SES	Stabilized Earth Specimens
SLW	Saturated Lime Water
SP	Strength Performance
SSS	Stabilized Sand Specimens
TGA	Thermographic Analysis
TGL	Trass+Gypsum+Lime
wt%	Weight Per Cent

1 Introduction

This chapter provides a brief introduction of the research background and the problem statement. Furthermore, the research objective, the research questions, the research approach, and outline for this thesis are outlined.

1.1 Research background

The discovery that soil can easily be formed and that it can serve as an effective building material responding to the requirements of habitability led to the development of mankind's oldest building culture. Today, the earthen construction is one of the most common construction techniques in the world and nowadays more than two billion people live in earthen houses [1]. However, the low resistance of earthen material to water and erosion, and especially the assumption that it could not be applied to form highly smooth surfaces and sharp lines in comparison to other modern constructions, have been and are still the most prominent reasons for choosing the new building materials. Moreover, decreasing costs and fairly wide spreading diversity of brick and similar products through faster production techniques caused a still prevalent process, in which, even up until even a few decades ago caused construction activity of earthen materials to all but stop

Nevertheless, after the economic crisis of the 1920s, earth as a building material came to the agenda again. Earth stabilization — which is in fact an old tradition — was finally scientifically defined for the first time and the term "soil stabilization" emerged. Since then, many studies have been carried out on soil stabilization. Soil stabilization for roads and airfields has come to the forefront, especially in the USA and England. 1970s Istanbul Technical University in Turkey, CRATERRA in France since 1980s, and Auroville Earth Institute (AVEI) in India since 1990s have made significant research on soil stabilization. The stabilization of the soil, by allowing the soil to maintain its ecological and building physical aspects, furthermore, has started to become a significant field of expertise that will enable the soil to stand out as an environmentally friendly alternative in the field of contemporary building materials, with improved properties of strength and durability.

1.2 Problem statement

The major drawbacks of earth such as low water stability and moderate strength have led mankind to stabilize the earth. It has been developed as a vernacular technique in different civilizations [2]. Lime is assumed to be the oldest stabilizer (Qingquan, Qing and Zhijing, 2004) [3]. Evidence of the use of pozzolans has been found in the Neolithic period (7000 BC) in

Galilee (Caijun 2001) referring to Malinowski et al.), the Minoan civilization (2700 to 1450 BC) (Carr 1995) and Ancient Greece (1500 BC) (Moropoulou et al. 2004) referring to Jiang and Roy [4]. The use of pozzolan with lime in masonry construction dates back to prehistoric antiquity [5]. Also, ancient Egyptians utilized gypsum in the construction of their pyramids [6]. With the increased interest in earthen material and with thanks to numerous research studies since the beginning of the 20th century, these additives were revisited, and new ones have been introduced in earth stabilization.

Recently, cement has become the most often used additive in earth stabilization as it is globally available, and it can significantly increase the strength and durability of plain earth. However, as is commonly known, cement consumption has serious environmental consequences. The main issue is that its production causes enormous CO_2 emission and thereby, contributes greatly to global warming. Not too long ago the 2016 Paris agreement once more underlined the target related to global warming. There is a growing consensus that overshooting scenarios for end of century temperature goals will require negative emissions [7]. Therefore, given the global effort to curb CO_2 emissions in an attempt to mitigate dangerous climate change effects [8] and the expected rise in global demand for cement, reducing emissions from cement manufacture presents an important challenge [9].

An environmentally friendly approach to substitute the cement with other additives in earth stabilization is needed. For this purpose, a variety of alternative materials with lower environmental impacts can be used. Their use is based on the importance of minimizing CO_2 emissions, as well as increasing interest in the production of cementitious materials that develop good mechanical properties and good stability in corrosive environments [10]. In this respect two concepts can be drawn from the literature. One is using artificial pozzolans as a partial cement replacement. For instance, the commonly used fly-ash is an artificial pozzolan, which is a by-product of CO_2 emitting burning processes. This concept allows the reduction of CO_2 emission but encourages, however, the sectors producing artificial pozzolana [11] — therefore causing just as much emission and even increasing environmental impacts such as water and land pollution. Also, as cement is being only partially replaced, the reduction of environmental impact remains at only a limited degree.

The second concept is based on using a combination of additives which are environmentally friendly or have lower environmental impact. However, there is a significant lack of knowledge and literature on this concept, and therefore, a lack of practical experience. Also, the newly introduced additives — for instance, new types of geopolymers — may not always be globally available. Their production is limited and costly.

Furthermore, in many cases attempts have been made by researchers to stabilize earth, which is not suitable for use in earth construction or production of earthen-based unfired materials. The choice and supply of earth planned for use in construction is then left to private investors or clients. This results in many cases, in the choice of unsuitable earth in order to rule out the time-consuming classification tests and survey due to extra costs. Also, many of these studies are focused on stabilizing earth for use in geotechnical applications.

In summary, there is therefore, need for concepts based on using environmental-friendly vernacular additives with the availability of prior- tested and classified earth.

1.3 Research objectives

The main objective of this study is to provide a method for lower environmental impact earth stabilization.

The main objective consists of the following five sub-objectives:

- The first sub-objective is to identify the specific research gap in earth stabilization, specifically strategies developed for substitution of cement in earth stabilization and to analyses the methodologies used in the field of earth stabilization. For this purpose, the current standards related to earthen building and studies based on different stabilization approaches have been discussed in detail.
- The second sub-objective is to determine the methodology based on data summarized from the research gap. The methodology includes the additives to be used in this study and the type and source of earth to be stabilized.
- The third sub-objective is to apply the method on mix-designs with varying additive combinations to investigate the effect of additives on the performance of stabilized earth specimens.
- The fourth sub-objective is to determine the CO_2 emission of the stabilized earth mixture with anticipated development to compare its environmental impact with cement. This will present the main advantage of proposed stabilization over cement stabilization.
- The fifth sub-objective is to define the gap in the earthen construction market through discussion of the usability of the developed stabilized earth mixture. The definition of the gap will allow the proposal of a novel product opening a new venue in the field of the earthen building sector.

If achieved, the proposed method will simplify the earth stabilization, so that the need of specific knowledge regarding stabilization can be reduced. It is designed with the aim to be applicable on a global scale as it is based on the rediscovery of easily available vernacular additives.

1.4 Research questions

In consideration of the main objective described in the previous chapter, the main question can be formulated as follow:

How can vernacular additives be combined to enable an efficient stabilization that allows the replacement of cement in earth stabilization?

The following sub-questions can then be derived from the main question:

Chapter 2:

1. **With respect to earthen building standards, which types of soils are suitable for earthen buildings and why is earth stabilization needed?**

1.1. Why is soil classification needed and which tests are being used to investigate the earth material?

1.2. How is the earth material being supplied today?

1.3. What is the state of earth stabilization and how is earth stabilization being classified?

1.4. What types of stabilizations are applied in the field and how do they function?

1.5. Which additives are the most commonly used and how available are they today? What are the benefits and deficits of their usage?

1.6. Which approaches are available to replace cement in earth stabilization?

1.7. How do the earthen building standards deal with earth/soil stabilization?

1.8. To what extend do earthen building standards deal with the types, effects, and ratios of stabilizing agents used for earth stabilization?

Chapter 3:

2. What are the main materials and investigation-based characteristics of the methodology related to the proposed stabilization?

2.1. What type of earth is being used for the proposed stabilization and how appropriate is the suitability of this earth for the proposed stabilization?

2.2. What are the main limitations of the proposed stabilization?

2.3. What were the selection parameters and limitations of the additives used in this study?

2.4. Which kind of tests are being used and for what purpose?

Chapter 4:

3. **Can an associate use of trass, gypsum and lime as an additive serve as an efficient and environmentally friendly form of earth stabilization?**

3.1. How do pozzolan, gypsum, and lime react with each other and with clay?

3.2. How does the proposed additives improve the properties of the earth?

3.3. What are the physical properties of the new stabilized earth in comparison to the plain earth?

Chapter 5:

4. **Which improvements are achieved over relevant studies and what are the advantages of using this mixture compared to conventional alternatives?**

4.1. What are the main developments achieved by the experimental results?

4.2. How much of a reduction in CO_2 emission is possible with the proposed stabilization technique?

4.3. How does the material behave with use? How is the workability of this product?

4.4. What types of earthen materials are available today and how is the market related to stabilized earth?

4.5. How is the developed mixture relevant on the current market related to earthen building materials?

1.5 Research approach and methodology

The research approach and applied methodology in this research can be summarized as follows:

Firstly, a comprehensive literature review was done beginning with a review of soil classification. Soil classification is needed to select the suitable earth planned to be used. Special emphasis was laid on earth stabilization. In the chapter Earth Stabilization, specifications and classification of both stabilization and additives used in the field, state of the art of earth stabilization were comprehensively discussed. Also, the current methodologies applied for testing the stabilized earth were discussed to provide data, which was necessary for determination of research specific tests. In the last part of the literature review the existing standards related to earthen constructions, specifically earth stabilization were reviewed and discussed. The review further helped to define the selection criteria and requirements for additives. Most importantly, the detailed literature review identifies a research gap.

Secondly, experimental programme was determined according to research done in the field. This programme contains the main experimental design used, the sample preparation and the laboratory tests to investigate the properties of the mix-design and the role of additives by replacement of cement in earth stabilization. This step presents the results of all the experiments that were carried out and the necessary data supporting the conclusions of these experiments.

Thirdly, all results drawn from experimental programme were discussed. This has been done through comparison of obtained results with the research done in the field. Moreover, the potential of the new earth mixture was discussed with regard to its usability in the field of building construction and architectural design and its environmental impact. The gap in the earthen building market was defined and finally, a proposal was made how to use the developed stabilized earth mixture on the market.

2 Review of state of the art

2.1 Review approach

The review consists of three parts. The first part of the literature review focussed on the classification and identification of soil and its mineralogy in order to define the criteria for the supply of raw earth material, which was needed for the experimental part. To do this the most prominent books and studies published by leading experts were reviewed. Their approaches related to classifications and testing — which have been accepted worldwide — were combined with each other, and summarized in the form of texts, table, and figures. This was necessary to determine which type of earth and which type of sources should be used for this study and what should be taken into consideration while choosing both the material and source of material. Eventually the type of earth selected for experiments was determinant in the choice of stabilization and additives.

To determine the proper additives and their reasonability for use in earth stabilization, the second part of the literature review focussed on earth stabilization. Through a collection of the most significant data included on several research studies and books currently published, it was possible to determine the current classification of stabilization techniques and additives. The advantages and disadvantages of common stabilizing agents, which are currently being used, were discussed.

In the third part, the current global earthen building standards were reviewed and compared with each other, as the standards describe the general boundaries of how to handle the discussed material. Various books and research studies published in the field refer to these standards. The review of standards helped to determine the terminology, definitions commonly used, and stabilizing agents referred to in particular standards.

2.2 Soil classifications and identification

Soil, earth, or clay? In many cases, the definitions for soil, earth or clay are commonly confused with one other. These terms have been described in many of the standards as mentioned in chapter 2.4. In this chapter they have been clarified according to standards and earthen building terminology. Following these clarifications, the soil classification and testing have been discussed.

2.2.1 Soil:

A granular material derived from weathered parent rock, often transported and sedimented by natural processes [12]. Soil consists of natural constituents such as humus[1], soluble salts and of gravel, silt, sand, and clay. Vitruvius describes soil as follows: some soils are earthy; others gravelly, and again pebbly; in other places the material is sandy; in a word, the properties of the soil are as different and unlike as are the various countries [13].

As the soil is an extremely variable material, it is recommended to analyse the proportions of clay, silt, and sand within the soil, before using soil for any kind of building purposes.

2.2.2 Earth:

A soil suitable for building purposes, which contains an appropriate mixture of silty, sandy and/or gravely particles, together with clay minerals as a natural binder and water, is classified as 'earth' [14].

2.2.3 Clay:

Clay cannot be very easily defined in precise terms [6]. Today in different sources almost identical definitions of clay can be found. Clay, when wetted, is the sticky material that bonds the soil particles together. An important point in this figure is that the boundary between sand and silt is 0.06 mm and smaller than 0.004 mm is clay. The current ISO[2] Standard 14688:1996 placed the boundary at 0.06 mm between sand and silt (Geological Society, London, 2006) [15]. According to ASTM, it is inorganic soil with particles sizes less than 0.005 mm with high to very high dry strength, and medium to high plasticity (ASTM 2005a) [16]. The clay content in the earth is different depending on the clay incidence[3] [17] and clay fraction of the soil and in particular the kind and amount of the respective clay minerals present, determines in large measure the chemical and physical properties of the soil [18].Therefore, in following section, some brief information is given on clay minerals and their classification.

2.2.3.1 Clay minerals and their classification:

In order to determine the suitability of soil for constructional purposes and to apply the proper stabilization it is important to project its nature. This may be possible if we understand the nature of clay within the earth. The clay fraction of the soil and in particular, the kind and

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[1] Humus is the organic content within the soil

[2] International Organization for Standardization

[3] Translation of the station from the German book: Lehm- und Kalkputze.

amount of the respective clay minerals present, determines in large measure the chemical and physical properties of the soil [18].

The clay is composed of different clay minerals, which have a crystalline, platelet-like structure throughout[4] [17]. Depending on the clay mineral, the platelets consist of several layers. One distinguishes between the two-layered minerals, such as kaolin and three-layered minerals, such as illite and montmorillonite [17]. See Figure 1. Montmorillonites or bentonitic soils are highly expansive when wet and when dry can shrink and crack. They are unsuitable for earth construction unless they are modified with sand. Other clays such as kaolinite, laterites, and illite do not swell and crack and can be appropriate for earth construction [16]. Also, ASTM reports that ideally, a non-expansive kaolinite clay should be used.

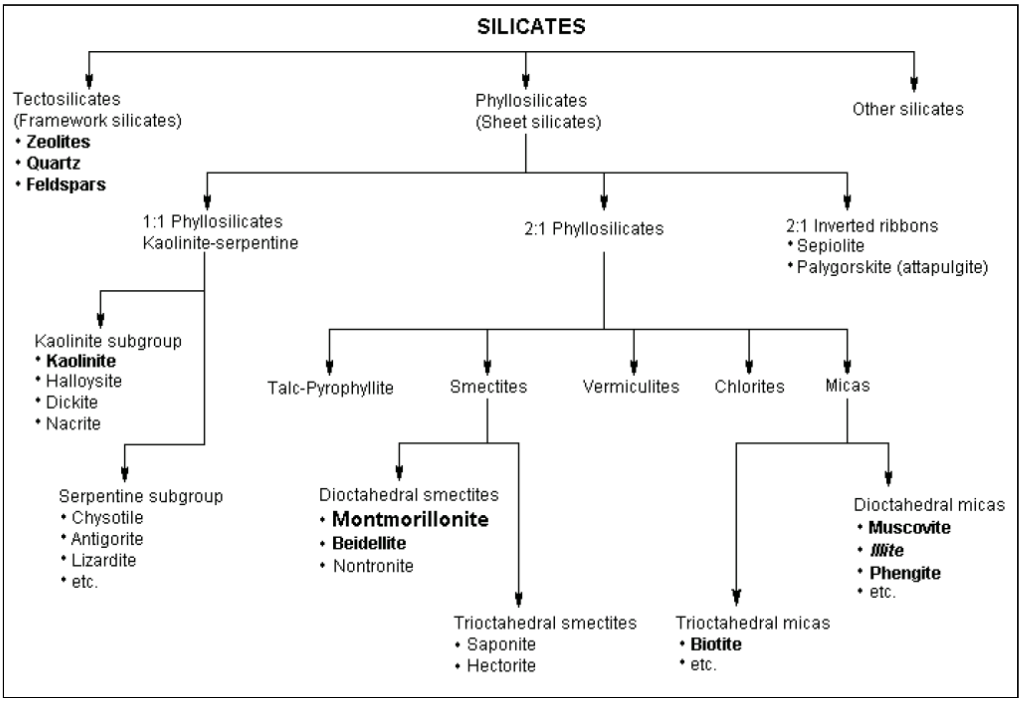

Figure 1: Classification of silicates and clay minerals (Bailey, 1980b; Rieder et al., 1998)[15]

2.2.4 Soil classification

Efforts have been made to classify soils for hundreds of years and no single classification is used throughout the world. The problems associated with particular classifications vary [19]. Soil Classification concerns the grouping of soils with a similar range of properties (chemical, physical and biological) into units that can be geo-referenced and mapped [20]. Special attention should be given regarding soil fraction. Then the percentages of textural fractions

[4] Translation from German book: Lehm- und Kalkputze.

are used as attributes to classify soils and as predictors to the estimate soil properties of parameters [21].

The more common classification systems can be listed as follow: a) Geological Classification b) Classification by Structure c) Classification based on Grain-size d) Unified Soil Classification System e) Preliminary Classification by soil types [20].

Houben and Guillaud (1994) recommend that the Engineering Geology Classification is the best suited to earth construction. Soils are classified by grain size distribution, plasticity, compactibility, cohesion, and quantity of organic matter [16]. Table 1 shows a classification system adapted by Van Damme et al. 2018 from ASTM 2487.

Table 1: Simplified Unified Soil Classification System with a qualitative assessment of the suitability for earth construction (Van Damme et al. adapted from ASTMD2487) [14] [22].

Major divisions			Group symbol	Typical soil names	Suitability for earth construction (unstabilized)
Coarse-grained soils >50% retained on the 0.075 mm sieve	*Gravels* >50% retained on the 4.75 mm sieve	Clean gravels, with <5% passing 0.075 mm sieve	GW	Well-graded gravels	Not suitable, fine soil should be added
			GP	Poorly graded gravels	Not suitable, fine soil should be added
		Gravel with >12% fines	GM	Silty gravels	Suitable but lacks cohesion and erodes easily
			GC	Clayey gravels	Suitable, sometimes fine soil has to be added
	Sands 50% or more passes the 4.75 mm sieve	Clean sands	SW	Well-graded clean sands	Not suitable, fine soil should be added
			SP	Poorly graded clean sands	Not suitable, fine soil should be added
		Sands with >12% fines	SM	Silty sands	Suitable but lacks cohesion and erodes easily
			SC	Clayey sands	Suitable, sometimes fine soil has to be added
Fine-grained soils >50% passes the 0.075 mm sieve	*Silts and clays* Liquid limit 50% or less	Inorganic	ML	Silts of low plasticity, silty fine sands	Suitable, but eventually lacks cohesion
			CL	Clays of low plasticity, lean clays	Sometimes suitable, sandy soil should be added
		Organic	OL	Organic silts and clays of low plasticity	Not suitable, sometimes acceptable
	Silts and clays Liquid limit larger than 50%	Inorganic	MH	Silts of high plasticity	Very rarely suitable
			CH	Clays of high plasticity, fat clays	Rarely suitable, sandy soil should be added
		Organic	OH	Highly plastic organic silts and clays	Not suitable
Highly organic soils			PT	Peat and other highly organic soils	Not suitable for construction

2.2.4.1 Output: criteria for selection of earth needed for stabilization

The chapter Soil classifications and identification provides the necessary information for determination of selection criteria of the earth needed for stabilization.

- One talks about earth or clay while dealing with earthen building planning or earthen building materials.
- Clays behave differently in the presence of water due to their variable chemistry, shape etc., and this behaviour affects the soil properties. Therefore, the type of clay is determinant while choosing an earth for building purposes.
- Earths with non-expansive clays should be used for building purposes.
- Clayey gravels, silty sands, clayey sands, or silty gravels are mainly suitable to use.

2.2.5 Soil testing

Soil testing is a significant process to determine its characteristics and its suitability of use in earth structure. However, majority of these test are not standardized, or even regulated [23] as discussed in chapter 2.4. Tests will reveal a soil's stability, permeability, plasticity, cohesion, compactibility, expansiveness, durability, abrasiveness, and material content [24]. Calkins (2009) stated that, test should be performed in three phases mainly property testing, construction mix and quality control testing. A very comprehensive grouping has been done by Houben & Guillaud (2014). A short summary of the tests according to these is shown in Table 2.

Table 2: Soil tests, a shorty summary from Houben & Guillaud [25]

Tests			
Identification analyses	Development	Performance	Characterisation
-Visual identification -Sedimentation -GSD -Limit of liquidity -Limit of plasticity -Proctor tests -Bulk density -Mineralogical identification -Natural moisture cont. -Specific area -pH -etc.	-GSD -Sedimentation -Bulk density -Wet and Dry CS -Tensile strength -Bending strength -Dry shrinkage -Water absorption -Erosion -Permeability -Fire Resistance -Swell -etc.	-Wet and Dry CS -Wet and Dry TS -Wet and Dry BS -Impact strength -Capillary rise -Water erosion -Wind erosion -Freeze-thaw -Swell and Dry -Shrinkage -Thermal expansion -Flow -etc.	-Compatibility with renderings -Fire Resistance -Specific heat -Thermal storage coefficient -Colour -Coefficient of conductivity -Surface texture -water absorption -Capillary -etc.
GSD: Grain size distribution, CS: Compressive strength, TS: tensile strength, BS: Bending strength			

Furthermore, control tests and acceptance tests can be conducted after identification and development tests to check the quality of material used in production and after production. However, as Houben & Guillaud mentioned: "*it should not be forgotten that the main object is to use the material for construction and not to carry out as many analyses and tests as possible*".

2.2.5.1 Output (criteria for determination of tests needed)

The output obtained from the chapter Soil testing is summarized as follows:

- There are currently no standardized tests in the field of earth stabilization. Tests can be defined based on research studies, with the aim to conduct only the necessary tests.
- Field testing and tests needed for identification analyses could be eliminated if an earth is used, whose identification is known.
- The evaluation process relevant for the study needs to be determined according to the Table 2 as given in 2.2.2.2, which will then form the boundaries of the tests useful for the study.

2.2.6 Supply of raw earth as building material

It is not yet possible to talk about a totally industrialized earthen building sector on a global scale. Except for some of the industrialised countries such as Germany, Switzerland, or France, in the majority of countries the extraction and processing of raw earth needed for construction is being done by clients using their own resources. The quarries are mostly chosen as close as possible to the construction site.

In some of the industrialised countries the extraction and processing of raw earth has been industrialized and specialized manufacturers provide different types of earths and clays with all necessary tests and classification. The material is packed and can be delivered in various quantities and forms.

2.3 Earth stabilization

2.3.1 Outline

The term soil stabilization was used at the beginning of the 20th century in regard to the stabilization of the soil, which was related to highway construction. There is a considerable amount of literature about the stabilization of the soil of highways especially from the USA. However, stabilizing the soil is not a modern method as mentioned in the following chapters. As the soil, which is suitable or has been improved for building purposes is called 'earth' in terms of architecture so also in this research it is meant 'earth stabilization or stabilized earth'.

2.3.2 Definition of soil stabilization and its classification

Soil stabilization is known as the process that enables the control of dimensional changes that clays suffer when they come into contact with water [28].
Rudolf Vincent Matalucci[5] distinguished soil stabilization in terms of construction procedures. According to this the soil stabilization was clarified as compaction, waterproofing, dilution[6], cementation and chemical stabilization. On the other hand, according to Murthy et al. 2016 this can be minimized and fall into two categories: mechanical and chemical stabilization. However, Houben & Guillaud’s (1994) categorization was based on three main categories, mainly mechanical, physical, and chemical stabilization, which more proper than Murthy’s and Matalucci’s approach.

Moreover, according to Puppala et al., stabilization methods can be classified as methods include use of calcium-based stabilizers (such as lime and cement), noncalcium-based stabilizers, and geosynthetic reinforcements [35].

However, as Ouhadi et al. stated, soil stabilization should not be considered just in terms of strength; in fact, to do so could cause serious structural failures [36]. Therefore, the proportions and combination of additives should be carefully investigated to prevent failures such as those caused by delayed ettringite formation etc.

1. **Mechanical stabilization**: refers to compaction, vibration or kneading of the material resulting in changes in its density, mechanical strength, compressibility, permeability, and porosity [25] [37]. It allows controlling the binder and water repellents [38].

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[5] Rudolf Vincent Matalucci “Laboratory Experiments In The Stabilization Of Clay With Gypsum“ May 1962

[6] Dilution: addition of other suitable soils for the attainment of a specified gradation. Matalucci 1962.

2. **Physical stabilization:** refers to changing the materials texture. This includes controlled mixing of different grain fractions or natural soils and mixing of fibres[23][37] (i.e. straw, animal hair etc.) into the soil.
3. **Chemical stabilization**: is the treatment of a soil with water-soluble salts to induce a chemical reaction [6], resulting with water insoluble compounds. It allows the dost control, water erosion-control and micro and macro structural stability [38].
   With regard to chemical stabilization, the clay particles can:

- Chemically bond with each other or bond with the added stabilizing agents, whereby new chemical compounds with or without clay or hydration products may occur (for instance stabilization with cement or lime etc.).
- Become captured with additives, so that they cannot interact or interact less with water molecules (for instance stabilization with bituminous materials, oils etc.).

Finally, the soil specimen turns into a,

- water- insoluble or less water-soluble,
- not swelling or less swelling form with,
- stabilized or decreased micro and macro-porosity, and with overall improved strength and durability.

A mechanically or physically stabilized soil specimen is still soluble in the presence of water, as it is not possible to efficiently reduce the micro voids and/or air voids and to chemically bind or transform the clay particles into a water-insoluble form or these stabilizations are not based on creating a water insoluble matrix (for instance a matrix of cementitious compounds). Therefore, this study is based on a chemical stabilization.

2.3.2.1 Aim of stabilization:

While mechanical stabilization allows controlling the binder and water repellents, the chemical stabilization allows the dost control, water erosion-control and micro and macro structural stability [38]. The aim of stabilization in general is, to preserve the positive features of earthen materials and processing methods in terms of building physics and to improve its inadequate mechanical and physical properties compared with highly stable modern building products [39].

2.3.2.2 Output

- The type (category) of the stabilization needs to be determined according to the aim of relevant study.
- Physically or mechanically stabilized earth will dissolve or swell in the presence of water, material may completely loose its stability and strength.
- According to the standards the term “stabilization” mostly refers to chemical stabilization. Therefore, if both water resistance and strength is aimed to be improved a chemical stabilization is necessary.

2.3.3 Additives used for earth stabilization

Laboratory studies of the means for changing the soil properties, and the search for a useful application of diverse industrial and trade wastes, have led to many proposed methods for soil stabilizations [40].

Lime, gypsum, natural and artificial pozzolans, animal blood [41], cow dung, urine, etc. have been used as stabilizer for hundred years in the earthen architecture history.

Murthy et al. 2016[7] classified the stabilizing agents as

- traditional and
- non-traditional.

This classification is based on additives, which basically change the chemical structure of the added soils.

According to this classification cement, gypsum, lime, fly ash, and bituminous materials are traditional stabilizers, whereas, chlorides, clay additives, electrolyte emulsions enzymatic emulsions, lignosulfonates, synthetic-polymer emulsions, and tree-resin emulsions are the non-traditional stabilizing agents. However, within a historical perspective, cement and fly ash cannot be classified as a traditional stabilizer. Therefore, this classification has been updated as given in Table 3.

[7] Murthy et al. “Chemical Stabilization of Sub-Grade Soil with Gypsum and NaCl” 2016

Table 3: Classification of stabilizing agents used in earth stabilization[8]

Traditional stabilizing agents	Non-traditional stabilizing agents
gypsum, lime, natural pozzolans (volcanic ash, tuff, trass), burned brick powder, bituminous materials, cow dung, animal urine	artificial pozzolans, cement, salts, calcium chloride, magnesium chloride, sodium chloride, clay, filler, bentonite, montmorillonites, electrolyte stabilizers, ionic stabilizers, electrochemical stabilizers, acids, enzymatic emulsions, enzymes, lignosulfonates, lignin, lignin sulphate, lignin sulphides, synthetic-polymer emulsions, polyvinyl acetate, and vinyl acrylic, tree-resin emulsions, tail-oil emulsions, pine-tar emulsions

2.3.4 Status of research in the field of earth stabilization

The soil stabilization, especially in countries like the USA, France, India, Australia, Spain and recently in Switzerland has been an important research subject and succeeded in testing earthen constructions as a significant alternative against highly energy consuming new products. Although there is a remarkable growing interest on earth architecture and a growing marked based on contemporary building products made of unfired earth, it is important to note that there is a big gap[9] regarding earth stabilization in German literature.

Stabilization is very ancient and since ancient times, small proportions of lime [28], pozzolan and gypsum were used in combination with earth. The first soil stabilization tests were performed in the United States in 1904. Cement was introduced as a stabilizer to construct a street in Sarasota, FL, in 1915 (ACI 1997), and lime was first involved in short stretches of highway with the expansion of roads to cater for the growth of vehicle traffic in 1924 [42] [43]. Cement stabilization was developed independently in Germany in 1920 [44]. It was only in 1920 that a scientific approach could be developed; major research was carried out in the three decades after Second World War and soil stabilization is not an exact science despite the research effort [44]. The special emphasis of research is on lime, cement, gypsum stabilization and stabilization with pozzolanic additives and since then a significant number of publications have been occurred.

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[8] The table is based on the classification done by Murty et al's paper (2016) "Chemical Stabilization of Sub-Grade Soil with Gypsum and NaCl" pp 572.

[9] Soil stabilization is not preferred in Germany.

According to literature recherché the soil/earth stabilization in general refers to chemical stabilization. As this research also investigates the stabilization effect of water-soluble salts, the following chapter Status of Research in the field includes only the state of chemical stabilization.

2.3.5 State of art

Yet, lime is the oldest stabilizing agent used in the world (Qingquan, Qing and Zhijing, 2004) [45]. It is the most common additive used in combination with many other additives. After 1950s lime was often used for the stabilization of pavements, roads, foundations and recently started being used for stabilized earth blocks, rammed earth, plasters etc. alone or in combination with other additives. Lime stabilization is since then the most researched subject in the field. Moreover, lime addition has been the most common technique [46], for stabilization of expansive soils with the aim to control the volume change. The mechanism of soil-lime stabilization was projected in detail by McDowell (1959)[3] and Diamond et al. in 1965 [47]. From clayey to sandy loam about 3 to 8% lime addition is required for an efficient stabilization (Minke 3-5% [48], Houben&Guillaud 3-8% [25]).
Ciancio et al. [49] researched the identification of optimum lime content for lime stabilized rammed earth and quick methods for identifying the optimum lime content [50]. Jawad et al. (2014) comprehensively discussed the advantages and disadvantages of soil stabilization using lime [51].
The effect of freezing and thawing on the strength and permeability of lime-stabilized clays was investigated by Yildiz et al. (2012) [52]. They stated that, freezing thawing does not stop the pozzolanic reaction; however, it retards the reaction in the clay soil stabilized with lime. Bhuwaneshwari et al. 2013 [53] and Leite et al. 2016 [54] have shown that swelling potential and plasticity of such soils can be significantly reduces with the help lime stabilization.
Landrou et al. [55] have shown that small amount of lime can efficiently be used as anti-plasticizer to reflocculate the clay. It is used to reduce swelling potentials (i.e., Martinez Belchior et al. 2017). Based on a study in 1970’s sponsored by US Air force Little (1999) reported that candidate soil for lime stabilization should possess at least 25% minus 75 micron material and have a PI[10] of at least 10 [56].
However, lime stabilization has some deficits. Using large quantities of lime for stabilization purposes, is environmentally disadvantageous, due to CO_2 emission of lime production. Moreover, lime increases the plasticity and workability of the earth, but lime stabilization is

[10] Plasticity index

based on long-term reactions, therefore, the expected strength development and water resistance is very much time dependent in and according to Wild et al. may cause durability problems [57]. Therefore, further strategies have been investigated such as using lime with pozzolanic additives (furnace slag, fly ash etc.), cement or gypsum.

Lime-pozzolan stabilization is probably one the oldest stabilization techniques and lime-artificial pozzolan stabilization has been the most investigated one. The mechanism lime-fly ash stabilization was investigated by McDowell (1959)[3]. Firoozi et al. stated that, lime and fly ash are a good combination for stabilizing silty and sandy soils. It drastically increased the stiffness of the final product [43]. However, pozzolanic reactions caused by lime-pozzolan stabilization are also time dependent and long-term reactions, therefore, chemical activation methods have been developed and widely studied (Xu et al. 1991, Owens et al. 2010) to increase the pozzolanicity pozzolan (for instance fly ash) mixtures.

Using lime with cement has also been investigated. According to Mahedi et al. cement and lime are the most commonly used stabilizing agents for treating expansive soils [58]. However, researchers (Rasheeduzzafar et al. 1994; Santhanam et al. 2003, Mahedi et al. 2020) criticized cement-lime stabilization due to secondary gypsum and ettringite formation.

Using lime with gypsum has been investigated by Kafescioğlu et al., Acun et al. 2003 [59], and Işık et al. In 1970s Kafescioğlu has investigated the properties of gypsum-lime-earth mixtures and called this mixture as Alker[11]. A comprehensive research was done by him and published in 1980 [60]. Since then, several experimental houses were built in Turkey, to investigate the physical and mechanical effects of gypsum and lime addition. Işık et al. (2011) [13] and, Pekmezci et al. (2012) [61] published paper showing the performance of earth structure by using lime (2,5-5%) and gypsum (8-10%) addition. According to these studies, gypsum-lime stabilization improves the water resistance of earth and the casting and compaction should be done in at least in 20 minutes. However, in this study, the soil suitability in terms of clay minerals was not taken into consideration. They recommended the investigation of freezing and thawing effects on samples containing lime-gypsum. Also, in 2007, Vroomen [62] researched the properties of cast gypsum-stabilized earth. According to this study, a great advantage of gypsum over cement is that it can be produced locally by small-scale enterprises and it demands a low amount of energy in production as it can be calcined at approx. 125°C instead of 1100°C. In addition, Islam et al. (2011) [63] investigated the earthquake resistance of adobe with gypsum, cement and natural fibre addition in respect of low cost materials.

[11] Alker consists of 10% gypsum, 2-2,5% lime and earth and is a kind of stabilized earth mixture.

It is important to note that, the principle of gypsum stabilization is based on strength development due to the hydration of gypsum and the recommended gypsum content for gypsum stabilization is around 5-10%. Gypsum content for earth stabilization can be further reduced if a proper concept strength development could be designed. Furthermore, the solubility of gypsum in presence of water can cause a loss of strength.

Moreover, since its discovery, cement became the most used additive in earth stabilization. Van Damme et al. [14] underlined that the recent trend by stabilization is most often the use of Portland cement (PC). Because;

- It is cheap and has a wide availability all around the world
- It significantly increases the strength and the durability of soil.

Especially from the beginning of 1940s cement became one of the most widely used additives in earth stabilization. For instance, in 1948 only in Karnal, Haryana, India 4000 rammed earth houses using 2,5% cement stabilization [64] were built. Since the development of the scientific approach, the most researched stabilization has become cement, and cement-lime stabilization. There is a remarkable number of publications and research projects in the field with various topics such as mechanical properties (e.g., Pongsivasathit et al. 2019), physical or dynamic properties (e.g., Chen et al. 2011), etc. of cement-stabilized soil. Cement stabilization is mostly applied by soil pavements, roads, compressed soil blocks, and adobe etc.

One of the prominent reasons using cement in earth stabilization is the high shrinkage of clay present in earth. Cement stabilization has been widely applied to reduce the shrinkage. George 1968 has done valuable work on shrinkage characteristics of soil-cement mixtures [65]. He found out that total shrinkage is primarily a function of the amount and kind of clay, montmorillonite contributing more than other types. Optimum cement content for stabilization suggested from researchers are 3-16% (Houben and Guillaud 1994[44]), 7-10% (Walker, 1995 [66], James et al. 2016 [50]), 5-10% (Riza et al. 2011[67]), 7,5% (Kabiraj et al. 2012 [68]). It can be concluded that, 5-10% cement is being used as an optimum content.

Moreover, the research on cement stabilization is recently very much focused on fibres with cement (e.g., Tran et al. 2018), influence of geopolymer (e.g., Deng et al. 2016) by cement stabilization, engineering characteristics (e.g., Kawasaki et al. 1978, Tang et al. 2000) of cement stabilized earth and thermal conductivity (e.g., Zhang et al. 2017).

In addition, another relevant issue today is the environment. Sofi et al. [69] investigated stabilized earth with 0%, 3%, 6%, 9%, 12%, 15% and 18% cement addition in terms of its economic and environmentally friendliness.

However, cement stabilization is being criticized due to following drawbacks:

- It is well-known fact that manufacture of OPC contributes to a lot of CO_2 emissions, which cannot augur well for a low-cost green material [50]. Using cement does not comply with the international target based on reduction of cement consumption and therefore, the CO_2 emission.
- It is well established that using Portland cement to stabilise clayey soils does not always produce the expected enhancements in terms of material performance [49]. One reason is, sulphate expansion [57] associated with delayed ettringite formation.
- Dahmen (2015) pointed out that, cement stabilization not only negates the reduced carbon footprint and embodied energy of earthen materials (Treloar et al. 2001; Reddy and Kumar 2010; Lax 2010; Arrigoni et al. 2017b), but the recyclability of the material after its service time is also debated (Pacheco-Torgal and Jalali 2012; Kapfinger and Sauer 2015).
- Cement stabilization has a negative effect on the hygric properties as well (Arrigoni et al. 2017a) [37].

The drawbacks of using cement in earth stabilization forced researchers to develop further strategies:

a. Using artificial pozzolans as a partial cement replacement (for instance ACI[12] suggested use of fly ash [70]):

The use of fly ash (FA) has emerged as one of the potential alternatives for stabilizing expansive soils (Hoyos et al. 2011; Mahedi and Cetin 2019; Puppala et al. 2003a, b) [58]. Mahedi et al (2020) evaluated the performance of cement, lime and fly ashes in stabilizing expansive soils and stated that, the addition of Class C and Class F fly ash to soil-cement mixtures improved the performance of cement-stabilized soils by significantly lowering the swelling potential and reducing the delayed ettringite formation.

b. Using other additive combinations resulting in similar or better strength and durability performance:

Wild et al. investigated the effect of ground granulated blast furnace slag (ggbs) on lime and gypsum added kaolinite [57]. They reported that, ggbs to lime-stabilized kaolinite dramatically reduced the swelling of specimens in contact with water. They also added that, much more detailed work using a wider range of compositions in order to verify the proposed hypothesis is needed.

[12] American Concrete Institute

In 2011, Lopez et al. studied the chemical reaction between fly ash[13], gypsum, and lime. According to them when the fly ash and lime are mixed with water, there is no chemical reaction in the initial phase. However, with increasing curing time between the fly ash and the gypsum, a pozzolanic reaction begins resulting in formation of Ettringite and CSH. Their study has shown that compared to the clay-lime-gypsum mixture, large amounts of ettringite are formed in the clay-fly ash-lime-gypsum mixture. They have stated that the formation of the ettringite accelerates the pozzolanic reaction of the fly ash, which improves the early strength. Figure 3 shows the restructuring effect of fly ash published in the study of Lopez et al. 2011.

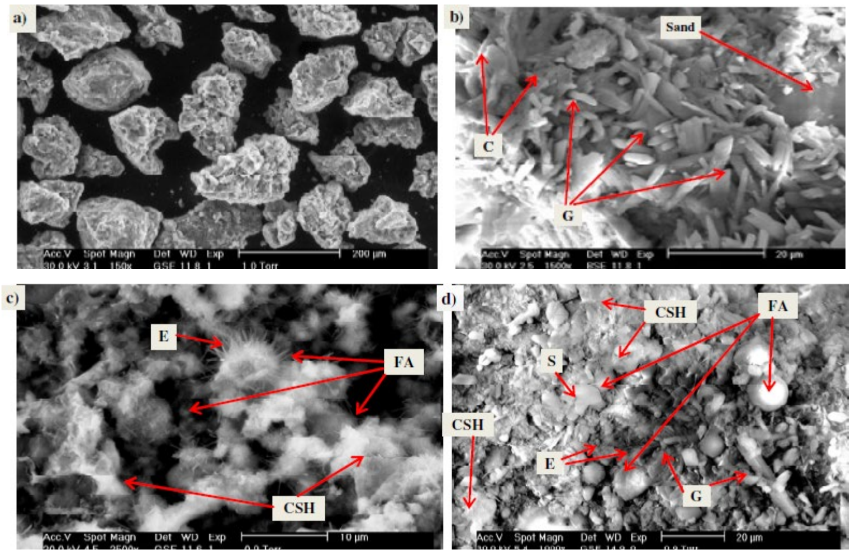

Figure 2: (a) Dark-brown soil particles; (b) Unfired compressed soil bricks without fly ash (DBS-LG) (c) and (d) Unfired compressed soil bricks with fly ash (DBS-FALG) (S, clay sheet; E, ettringite crystal; G, gypsum crystal; CSH, calcium silicate hydrate gel; FA, fly ash; C, Ca(OH)2) [71].

The needle-shaped gypsum crystals visible in Figure-b form a network in which the pozzolanic reactions and the hardening of the hydrated lime continue.

Another study regarding earth stabilization with gypsum, pozzolanic additive (ferrochrome slag) and lime appeared in 2017 in Turkey. Türkmen et al. [72] used gypsum, ferrochrome slag[14] and lime as additive for traditional adobe called kerpiç[15] (it includes straw as reinforcement[16]) to determine the stabilization effect. They stated that the gypsum stabiliser indicated the higher compressive strength values compared to ferrochrome slag stabiliser.

[13] Fly ash is an artificial pozzolan by product recycled from the fabrics (see also glossary).

[14] Ferrochrome slag is an artificial pozzolan

[15] Kerpiç: a vernacular adobe used in Turkey. It is an unfired earth block with crushed straw and water.

[16] In Turkey, the straw is commonly being used for physical stabilization of the adobe bricks.

However, when compared to other samples, increase in compressive strength of specimens with only ferrochrome slag is due to pozzolanic effect, higher.

Moreover, an attempt was made by Jha et al to study the efficiency of fly ash and lime on the volume change behaviour of a gypseous soil[17] with about 1 wt% gypsum to mask the effect of gypsum [73]. They observed that, the formation of cementitious compounds with a curing period enables to the compound to overcome the adverse effect of ettringite, leading to control of undesirable volume change behaviour.

In 2018 Roesyanto et al. used in a study regarding to clay stabilization, fixed percentage of gypsum (2%) with 3-15% of volcanic ash[18] [74]. However, the strength improvement they recorded was not significant, which may be due to lack of Ca^{+}.

Gadouri et al. 2019 [75] studied the effect of the interaction between calcium sulphate and mineral additives on shear strength parameters of clayey soils. They stated that the mineralogical composition of soil has a capital importance and plays an important role in the stabilization process success and $CaSO_4 \cdot 2H_2O$[19] can be used in civil engineering projects as an accelerator of chemical reactions between soil, lime, and natural pozzolana.

[17] Soils containing gypsum.

[18] Trass is also a kind of volcanic ash

[19] Calcium sulfate dihydrate

2.4 Earthen building codes and standards

In global terms construction is very much controlled by regulation, and regulation in turn has become the guardian of industrial products and process [76]. However, generally, building with earth has not been considered as an "engineered construction technique" in the past and thus building standards were considered unnecessary [77]. It suffers from a poor image and from the difficulty to meet modern productivity standards and to pass some durability tests designed for industrial materials [14]. Nevertheless, this is changing and one can safely say there is notable progress in the field, because, earth construction is not only dependent on adequate training but also on specific regulations [78]. Therefore, in this chapter the current standards on earth material and earthen buildings have been reviewed.

2.4.1 Earthen building standards and codes:

Earthen building systems have historically not been engineered [26]. We only have evidence showing that there were some form of guidelines. For instance, archaeological excavations have proven that the Egyptians described the brick making on the clay tablets as shown in Figure 1.

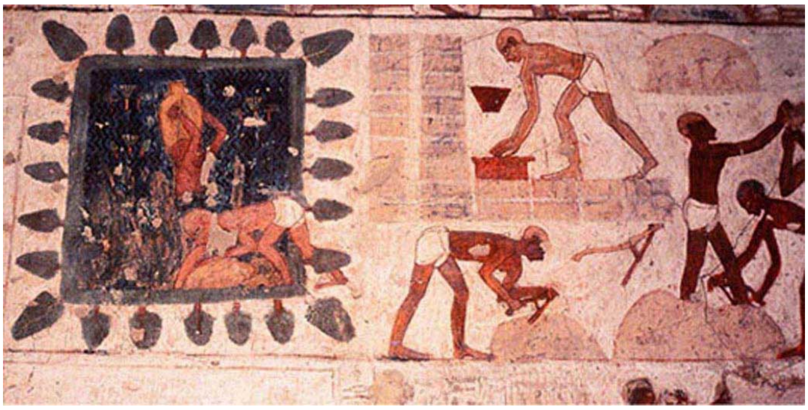

Figure 3: Adobe making fresco, Thebes, Tomb of Rekhmire, Egypt. 15th Century BC [27]

Also, Vitruvius[20] described in his book "The Ten Books on Architecture"[21] the kinds of clay suitable for sun-dried bricks. He mentioned the optimal seasons for sun-dried brick productions and the explained fundamental reasons behind this logic. He also described the kinds of bricks. However, the "forest regulations", which were mostly short excerpts from

[20] Vitruvius was a Roman architect.

[21] The book is one of the oldest books on architecture

provisions and published since the beginning of 18th-century in Germany and Austria [15] are being mentioned as the oldest preserved written standards for earthen buildings in today's perspective.

But as of the late 20th Century it is for the first time in history possible to reliably apply rational structural design methods to earthen construction [26].

Today, in countries like Germany, France, New Zealand, Peru, Australia, earth construction is strongly regulated and supported by appropriate policies and actions [28]. Recently in South Africa, Zimbabwe and Mexico standards for the construction earthen walls have been approved. However, the first country, which has regulated the soil constructions, was Australia in 1952 (ROM p151)[22]. Standards Australia published "Australian Earth Building Handbook (HB 195-2002)" as unofficial guidelines.

In Germany, the National DIN[23] standards for earth blocks and earth mortars (DIN 18945, 18946 and 18947) were introduced in 2013 [29]. New and revised DIN codes on earth building products were published in December 2018 [30]. DIN 18942-1 earthen materials and products, DIN 18945 earth blocks, DIN 18946 earth masonry mortar, DIN 18947 Earth plasters and DIN 18948 earthen boards. The standardization of earthen boards is a significant progress as these products are firstly being standardized, although they are being used for more than two decades. These national standards follow the general and basic requirements for the formulation of European regulations for building products defined in the European Regulation No. 305/2011 concerning harmonized conditions for the marketing of construction products in the EU[24] (Construction Products Directive CPD) [29]. However, there is still no comprehensive EU Standard for earth buildings.

Moreover, in Switzerland "*Regeln zum Bauen mit Lehm*[25]"[31] was published by SIA in 1994. Detailed information on the classification of earth material can be found in this publication. In the USA, the current edition of earthen building standards E2392/E2392M were approved in 2010 and called as "Standard Guide for Design of Earthen Wall Building System" [26]. The ASTM[26] used New Zealand Standards as reference. In New Zealand, Engineering Design of Earth Buildings (NZS 4297:1998), Materials, and Workmanship for Earth Buildings (NZS

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[22] Article paper: Construction sustainability with adobe bricks type elements.

[23] Deutsche Institut für Normung (German Institute for Standardisation)

[24] European Union

[25] Rules for Building with Earth

[26] American Society for Testing and Materials

4298:1998) and NZS 4299:1998 are the current standards. In India Specification for Soil-Cement Blocks (IST 715) is published by Indian Standards Institute.

Also, for instance in Italy, where the regulations seem to be not sufficient, researchers begun to define new guidelines for rammed earth restoration [32].

In Japan there are no regulations specified for earthen buildings. The Adobe bricks or earthen buildings should comply the masonry building regulations of BSL (The Building Standards Law) of Japan. Turkey's first standard about earthen buildings, respectively adobe blocks, has appeared in 1977 as TS 2514. In 1985 another standard appeared; TS 2515, which was about the buildings planned and constructed with adobe blocks. However, these standards were withdrawn in 2011.

Last but not least, the study "building normative documents in the world" [33] published by Cid-Falceto et al. (2011) provides detail information on standards worldwide.

2.4.2 Earth stabilization in Standards

The term "stabilization" is being mentioned in many of the above-mentioned standards and regulations, however, not in a unique form. For instance, ASTM 2392/E2392M−10 or NZS clearly defines and differentiates the terms "stabilization" in chemical means and "stabilized earth" where the earth is handled as a raw material. Cement, lime, gypsum, and asphalt are also mentioned as some of these stabilizers. Also, NZS 4297:1998, determines the terms stabilization and stabilizer and the stabilized products and earthen building elements referring, however, only to its cement addition. DIN 18945 on the contrary, defines only the term "stabilized unfired earth bricks". New Mexico Earthen Building Materials Code uses the term "amended soil" (improved soil) and "amendments"[34] (additives).

The most widely mentioned stabilization and therefore more comprehensively standardized one is cement-stabilization. Therefore, in many of these standards (for instance ASTM, DIN, TSE[27] or NZS[28] etc.) descriptions of tests are attributed to cement-stabilized soil. For instance, freeze-thaw and wetting-drying tests in regard to cement stabilized soil blocks has been determined in ASTM in 1965, Indian Standard IS 4332 (Part IV) 1968 and in TSE 1978. In India, the production of cement stabilized, and compressed earth bricks is today quite common.

Australian HB 195-2002 categorizes the test as field and laboratory tests. Shrinkage, water absorption, compressive strength, accelerated erosion test or dry density are one of these

[27] Turkish Standards Institution

[28] Standards New Zealand

tests. NZS 4297:1998 categorizes durability, strength, and shrinkage as performance criteria. in Switzerland “*Regeln zum Bauen mit Leh*m” (SIA 1994) lime, cement, bitumen, and synthetics are mentioned as stabilizers.

2.4.3 Output

It has been determined that the review of earthen building standards has provided only basic information on soil selection, stabilizers, and the scope of tests used for the determination of properties of stabilized earth.

2.5 Summary of review and research gap

2.5.1 Summary of review

The results drawn from the review of state of the art is as follow:

- Earths with non-expansive clays should be used for building purposes.
- Clayey gravels, silty sands, clayey sands, or silty gravels are mainly suitable to use.
- earth stabilization is being accepted as a significant research field to improve the common drawbacks of earth material
- there is no unique and internationally accepted terminology for earth buildings and earthen materials.
- the earthen building standards describes the principles of earthen building but mainly adobe or rammed earth buildings
- no significant information on types of stabilization and types of stabilizers. Basically cement, lime, fly ash, gypsum are being mentioned as common stabilizers. However, there is no common classification and determination of the types of stabilizers and their limitations of use. For instance, stabilized earth bricks (SEB) are mentioned in DIN addressing the cement stabilization and efficient amount of that; however, types of other stabilization, their methods, limits, and targets are not defined.
- According to the standards the term "stabilization" mostly refers to chemical stabilization. Therefore, if both water resistance and strength is aimed to be improved a chemical stabilization is necessary.
- cement stabilization is the most commonly standardized and addressed one. Standardization of ecological stabilization methods is needed.
- the technical information in the different standards varies widely and no uniform and internationally accepted laboratory tests exist for the moment [77]. The tests are mostly based on products made of earth but not plain earth or earth-mix as raw material. Mostly cement testing standards are being used. Durability, strength, accelerated durability and water absorption tests are the most common tests addressed in standards soil specification and the soil types suitable for earth stabilization are very insufficiently discussed. The additives used for stabilization, their affects and classification are not discussed.

Typically soil for building purposes is being supplied from a local source closed to the construction field.

- It is being excavated, transported, and then crushed for sieving to a certain grain size (this process is called soil processing)
- or the earth from an existing earth building ruin close to a construction site is being crushed and reused.

However, for a couple of decades companies existed as suppliers of various types of earth products such as different types of clay or ground earth in different sizes of bags. It is possible to order the earth material needed for planned use. As an industrial product the companies declare the composition of the material, its granulometry, type of clay and its properties etc. so that the material can be used as an identified and characterized product. Field testing and tests needed for identification analyses could be eliminated if an earth is used, whose identification is known.

2.5.2 Research gap

As stated in chapter 2.3.5 cement is still being widely used in earth stabilization. Wild et al., Lopez et al. and Gadouri et al. stated that lime-pozzolan-gypsum combination could be a significant alternative to cement in earth stabilization. However, there is still a significant lack of knowledge in the field of lime-pozzolan-gypsum stabilization. For instance, as pozzolanic additive mostly artificial pozzolana (fly ash, furnace slag etc.) is being used and the effects of natural pozzolana have not yet been studied. Also, there are three critical disadvantages of using artificial pozzolana:

- their production and availability are seasonally limited,
- their usage encourages the sectors producing by-products of burning processes and therefore, contributes to environmental impacts.
- The pozzolanicity of the various artificial pozzolana from different burning processes need to be determined, which is associated with great expenditure.

Jackson et al. [79] reports, with the current decline in coal-fired energy, fly ash is now becoming technically and/or economically unfeasible for use in concrete. Furthermore, artificial pozzolans result from chemical and/or structural modifications of original material, which may have weak pozzolanic characteristics, or not. On the contrary, natural pozzolans do not require any treatment before their use [71].

Investigations have been conducted on the stabilization of soils containing natural sulfates (Wang 2002 [42], Jha et al. 2016 [73]), however, these studies are geotechnical studies and not with the aid of building construction.

Finally, the most relevant publications for this thesis found by recherche, are Wild et al. "Effects of ground granulated blast furnace slag (ggbs) on the strength and swelling properties of lime-stabilized kaolinite in the presence of sulphates" published 1995, Lopez et al.'s study with the title "Effect of fly ash and hemihydrate gypsum on the properties of unfired compressed clay bricks" published in 2011 and Gadouri et al. 2019 "Effect of the interaction between calcium sulphate and mineral additives on shear strength parameters of clayey soils" published in 2019. However, there are the following gaps in these studies:

- Wild et al. use pure clay (kaolinite) without sand, which is not suitable for construction. They also used artificial pozzolan.
- Lopez et al. use a local soil, which needed to be classified in terms of suitability and its properties. Also, the soil they used was an expansive soil (montmorillonite) and therefore, not suitable for constructional purposes. They used an artificial pozzolan.

- Gadouri et al. used both expansive and less expansive local soils that needed to be classified. They focused primarily on the sheer strength and cohesive character of the mix-design proportions.
- No performance tests (such as freeze-thaw, water resistance, wet CS etc.) were conducted in these studies.

3 Methodology for mix design development

3.1 Experimental program design

Based on the research objectives and scope as well as the information from the literature review, an experimental program was organized into the following components:

- Preparation of industrial earth and its identification
- Experimental studies of industrial non-expansive earth mixed with natural pozzolan, lime, and gypsum in order to both develop an earth mixture with improved strength properties and to develop an environmentally friendly method to replace the use of cement in earth stabilization.

The flow chart with the particular steps of this study's beginning with the main research question is given in Figure 4.

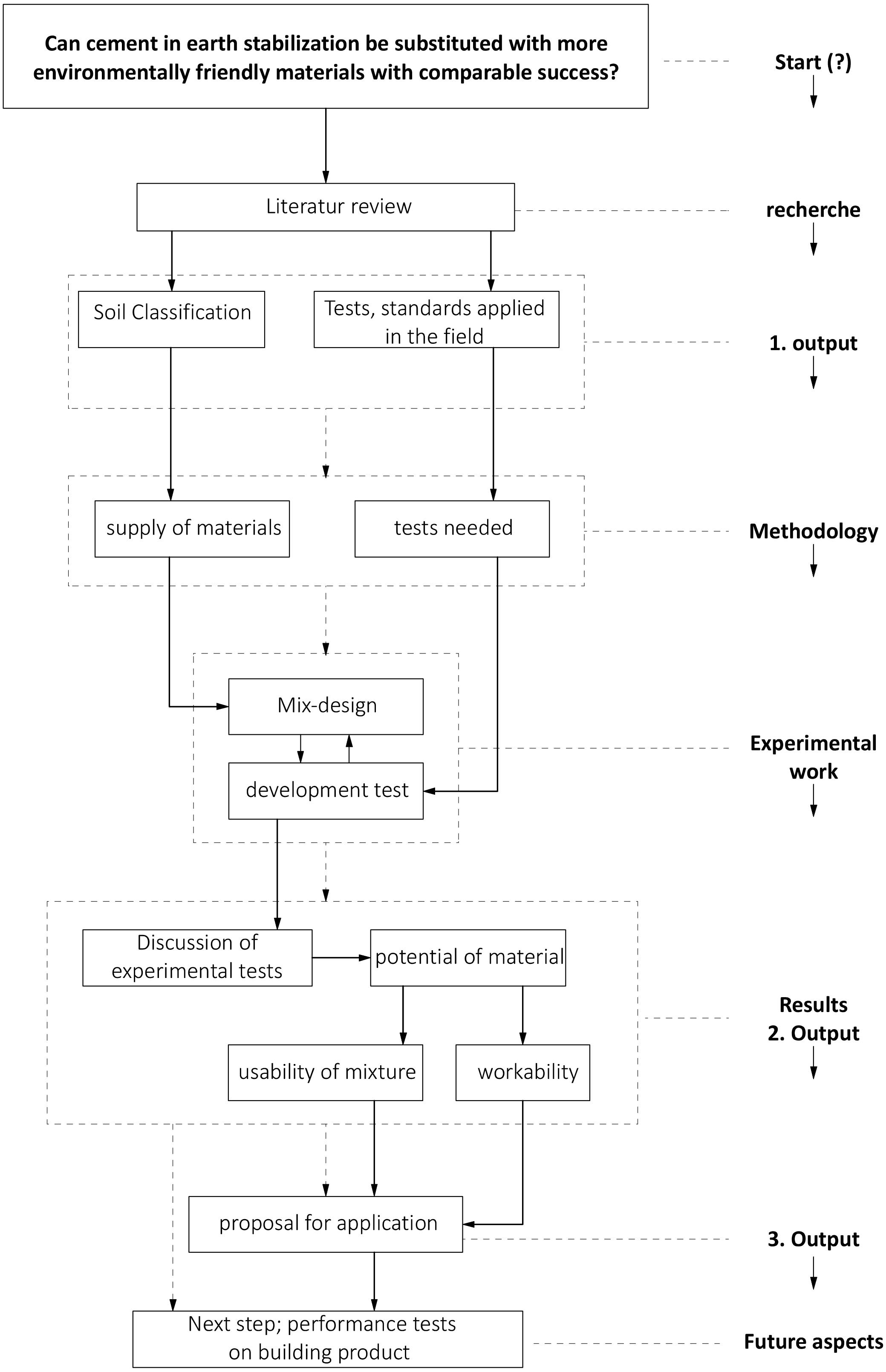

Figure 4: Flow chart of testing Methodology of ETGL

3.2 Methods

The methods of the development process of the mix-design including materials and procedures are given below:

3.2.1 Materials

3.2.1.1 Earth:

The earth needed for experiments was made under laboratory conditions, consisting of industrial clay and industrial standardized sand. A typical flow chart of supply, classification, testing and the manufacturing process of an earth material adapted from Krosnowski 2011 is given in Figure 5. As can be seen in Figure 5, the industrial earth made it possible to eliminate soil excavation, classification, and soil suitability tests, as the identification and characterisation of supplied material is being delivered by the manufacturer.

Işık et al. mentioned that the required binding property can only be achieved if earth has 30-50% clay content [80]. Moreover, Woyciechowski et al. 2017 [81] used an earth containing 70% of aggregate and 30% of loam. Based on further researches, the best possible combination of ingredients would be 70% of sand and gravel, and 10% to 20% clay in the obtaining of good wet compressive strength of blocks (Olivier and Mesbah, 1987; Houben & Guillaud, 1994; Venkatarama Reddy and Jagadish, 1995) [82].

In this study the percentage of clay and sand within the earth was kept at 30% clay + 70% sand as reference by all experiments.

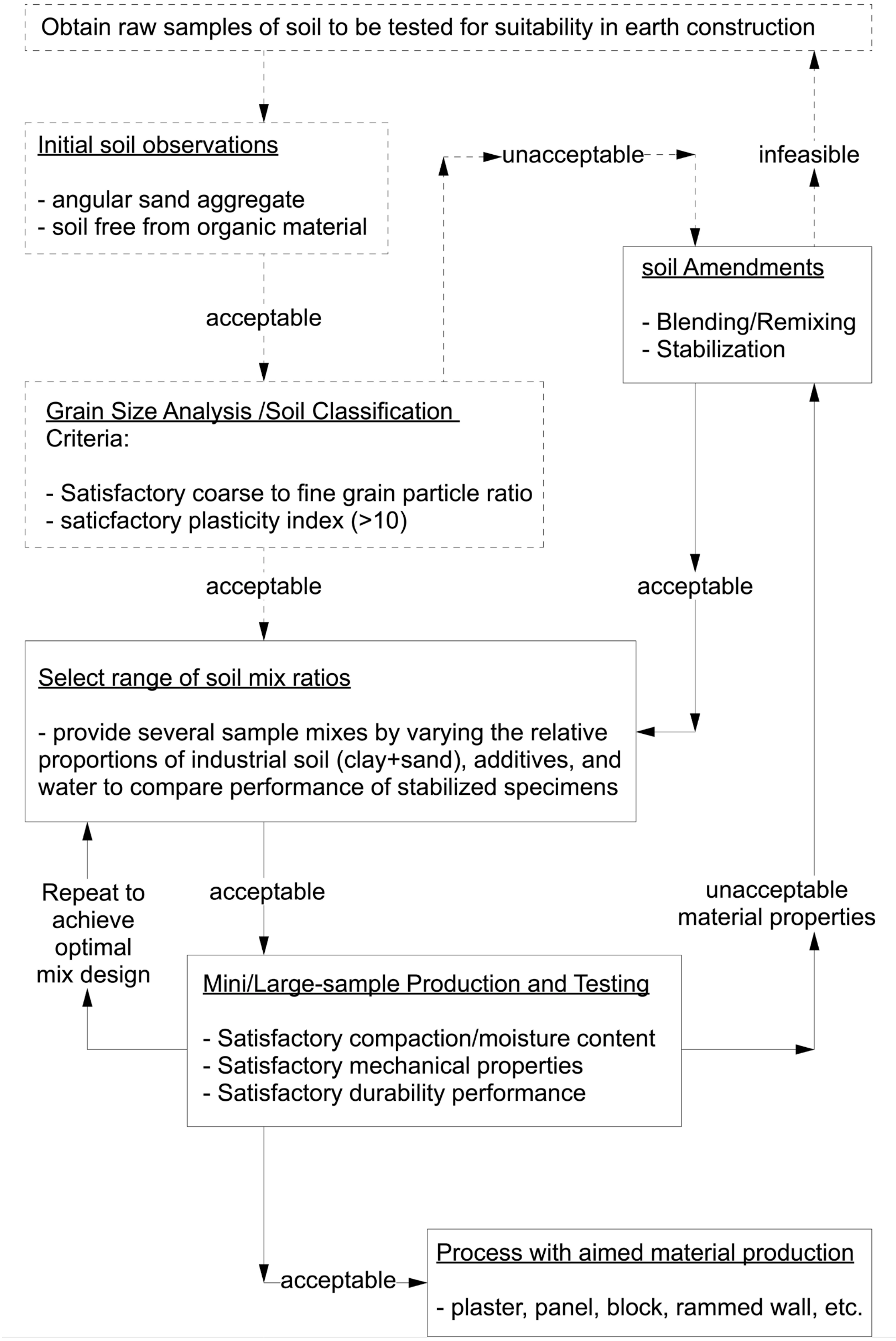

Figure 5: The typical flow chart of testing and manufacturing process of an earth material. The flow chart is adapted from Krosnowski 2011 [83].

3.2.1.2 Additives:

The additives used to stabilize the industrial earth were determined as given in chapter 3.3.1. The selection boundaries were based on the research gap. These additives are classified as traditional additives available on the market and are as follows:

- Hydrated lime.
- Trass (a grounded natural pozzolanic earth)
- Hemihydrate gypsum.

Detailed information on additives used for the tests are given in chapter 3.3.1.

3.2.1.3 Mixture:

To investigate the effect of selected additives, stabilized test specimens were prepared with various additive proportions. These proportions are given as a table for every specific test in the related chapters. Where the total percentage of additives kept by 20,5 wt% of the total dry mix, the trass and gypsum content varied between 0-18 wt%. Wild et al. kept in their study the gypsum content by 4 wt% as reference [57]. However, in this study lime content was kept at 2,5 wt% as reference value, as the study is based on sulphate activation.

Mixing, casting, and drying processes were done under laboratory conditions of a 23°C temperature and 50% relative humidity. For casting the specimens DIN-EN-196-1 steel moulds with dimensions 160x160x40 mm were used, which are commonly used for cement mortar testing (see Appendix B).

Kafescioğlu et al., Pekmezci et al., and Işık et al. used 16 wt% and Lopez et al. 20% water as the sufficient amount of water for stabilized specimens. In this study, 20 wt% water was used as a reference amount, as this amount of water was sufficient to cast the specimens without the need of compaction.

3.2.2 Testing procedure:

Testing procedure consists of two steps: development and performance tests, where the aim of development tests was mainly;

- to optimize mixture proportions
- to characterize the stabilization effect
- to identify the pozzolanic reaction products,

the performance tests were conducted to investigate the performance of the developed mix-design under extreme conditions such as presence of water or sulphate and repeating freeze and thaw conditions.

As described in 2.3.2.3 the expected improvement in properties of earth with the proposed stabilizing agents is based on pozzolanic reactions and the pozzolanic activity can be determined by physical, mechanical, or chemical means. In this research, together with the development tests (workability, strength performance, XRD-Analyses, shrinkage, setting time, density) the performance tests (water resistance, freeze-thaw tests, delayed ettringite formation) were conducted as given in Table 4.

Table 4: The experimental test carried out in this study

Tests	
Development	Performance
-Slump -Grain size distribution -Sedimentation -Bulk density -Porosity -Wet compressive strength -Dry compressive strength -Flexural strength -Dry shrinkage -X Ray diffraction analyses	-Wet compressive strength -Dry compressive strength -Capillary water rise -Water erosion -Water absorption -Freeze-thaw cycle -Dry Shrinkage -Delayed Ettringite formation -VICAT setting time -Thermal conductivity

Firstly, a slump test was conducted to compare the workability of mix-design with varying trass/gypsum ratio. Koehler et al. stated that this test is widely used for the characterization of workability of the fresh concrete. The test method is widely standardized throughout the world, including in ASTM C143 in the United States and EN 12350-2 in Europe [84]. However, this test is recently also being used in the soil science.

3.2.2.1 Strength performance

Strength performance (SP) of mix-design was tested according to DIN EN 196-1 programmed in the testing device Walter + Bai 502/4000/100. SP test can be used as a significant method to determine the stabilization effect of the admixtures on plain earth. Walker (1997) stated that compressive strength test procedures for earth blocks generally follow those used for concrete and clay masonry units [85]. Also, Riza et al. underlined that the most universally accepted value for determining the quality of bricks is compressive strength (CS) [67].

The SP tests were performed mainly to study the effects of different binders on the increase in strength with time after stabilisation. A series of beam specimens with dimensions of 160x40x40 mm were used for the tests. The specimens were cast in a steel mould. The beams were firstly used to determine the flexural strength (FS). After the flexion test, the specimens were then divided into two prismatic parts. The compressive strength (CS) tests were conducted over each of these parts, following the standard UNE-EN 13286-41[29]. The samples were kept under laboratory conditions of at 23°C temperature and 50% relative humidity and left for drying.

Walker (1997) stated that minimum CS requirements are often specified using wet ('saturated') values, varying between 1.0 and 2.8 MPa [1,3-9] [85]. Because typically, determination of compressive strength in wet condition will gives the weakest strength value [67]. For this purpose, a series of stabilized earth specimens cured under laboratory conditions were firstly placed in a water tank and completely embedded into the water for 24 hours (see Appendix C). Secondly, the specimens were removed from the water tank. While one group of the specimen bars were pressed directly after removing from the tank, the other group were again dried under laboratory conditions for 28 days and then pressed.

Harichane et al. 2012 [86] have documented a significant improvement of SP by natural pozzolana and lime stabilized soil specimens. Hence, to better understand the stabilization effect on the improvement of CS, further compression tests were conducted. Moreover, the increasing water content in plain earth caused swelling and therefore, had a negative effect on SP. However, the complex interactions between the stabilizing agents and water makes the relationship between water content, dry density, and strength much harder to predict [87]. Therefore, the relationship between water content and CS was investigated.

According to Laguras et al. decreased solubility of lime at higher temperatures may account for at least part of the strength increase [88]. Also Hilt et al. stated that a certain amount of lime must be added to a clayey soil before cementing products, which will increase the strength of the soil can be formed [88]. Therefore, instead of using 2,5 wt% of lime, the saturated lime water (SLW) was used to further investigate the strength development. However, in this study the preparation of SLW was limited to only 23°C. The preparation of SLW is described in chapter 3.3.1.5. As, the content of stabilizing additives in total mix-design was always kept at 20,5 wt% of the total dry mix (additives + sand + clay), the dry lime content was filled with the equal amount terrasol (2,5wt%).

[29] Unbound and hydraulically bound mixtures - Part 41: Test method for the determination of the compressive strength of hydraulically bound mixtures (https://www.normadoc.com/german/une-en-13286-41-2003.html, accessed April 28th, 2021)

3.2.2.2 X-Ray diffraction analyses

The mechanism of stabilization is based on pozzolanic activity, which causes durability effect in an environmentally friendly way. To better understand this mechanism and to identify the products of pozzolanic reactions, the mineralogical composition of the mix-designs was analysed with the help of X-ray diffraction (XRD). Moore et al. (1989)[89], Lavina et al., (2014)[90], and many other researchers reported that XRD has become a commonly used technique for the identification and characterization of materials. Practical application of XRD and methods of minerals identification and estimation have been provided by Tucker, (1988); Carol, (1970); Thorez, (1976), and Zussman (1977) [91].

The samples for XRD measurements were made without sand or clay content. Only the additives (trass, gypsum, lime, NaOH) in different mix-design combinations were mixed with 20 wt% water. The samples were kept sealed under laboratory conditions of at 23°C temperature and 50% relative humidity and the fluid mass was then left to cure for 7 days and 28 days. The samples were then ground and sieved to a grain size of 20µm. Sample mounting was done with the help of special sample holders. The powders were mounted in these holders with the help of a razor blade. This method was developed at ETH-Zürich. Detailed information about sample mounting and preparation of powder samples for XRD measurement has been discussed and explained by Bish et al. 2011 [92]. Mineralogy of the samples is determined on randomly oriented powder specimens. The powder samples were step-scanned at room temperature from 4 to 80°2Theta (step width 0.02°2Theta, counting time 2 s per step). The qualitative phase analysis was carried out with the software package DIFFRACplus (Bruker AXS). The phases were identified based on the peak positions and relative intensities in comparison to the PDF-2 database (International Centre for Diffraction Data). The quantitative amount of the mineral phases was determined with Rietveld-analysis with the program Profex/BGMN [93]. The amorphous content not calculated by Rietveld but with DiffracEVA as (global area-reduced area)/global area. The chemical composition of most amorphous minerals is not as definite as that of the average crystalline mineral [94]. In this study, only the total amorphous content was calculated, not the chemical composition.

3.2.2.3 Shrinkage

Linear shrinkage is a significant parameter for determination of behaviour of stabilized earth mixtures. George 1968 [65], Chmeisse 1992 [95], Walker 1995 [66], Dang et al. 2016 [96], Pekmezci et al. 2012 and many other researchers used shrinkage measurement for investigation of the characteristic of stabilized soil material.

For shrinkage measurements Mitutoyo ABSOLUTE Digimatic 12,7mm 543-400B Serie 543 was used (see appendix E). The linear shrinkage measurements were done on 160x40x40 mm prismatic SES. Two different SES series were prepared: series with 16 wt% and 20 wt% water addition. The measurements were carried out over a period of 56 days. The specimens were kept under laboratory conditions of at 23°C temperature and 50% relative humidity.

3.2.2.4 Setting time

Setting time is controlled by many factors, such as used additives, heat, pozzolanic, hydraulic and/or cementitious reactions. It delivers significant information on material characteristics. For determination of the setting time of mix-design pastes with various proportions, the Vicat test was carried out. The Vicatronic Automatic Vicat Recording Apparatus was used (see Appendix F) for this purpose. The method is based on shearing cement paste with a needle, following the idea that stiffening during the set induces a gradual increase in resistance to shearing. The initial set is defined as the time at which the needle will not penetrate within a certain distance into the bottom of the mass, and final set as the time when there will be no mark upon the surface from the needle (i.e. no penetration of the needle) [97].

Romano et al. criticizes that the values obtained are empirical, useful only as a comparative basis, and not corresponding to specific aspects of microstructure formation during the initial hydration or the rheological parameters of suspensions (Lootens et al. 2009[30], Struble et al. 1995[31], Zang et al. 2010[32]) [98]. However, according to Amziane (2005) the Vicat test still remains today the most commonly used test by cement-manufacturers and is the subject of multiple standards (NF EN 196-3, ASTM C191-93, AASHTO T 131) around the world [97].

For the test EN-196-3, was selected, which is the standard for determining the setting time of cement, as currently there is no specific standard of measurement for the setting time of stabilized earth pastes.

Mehrotra et al. 1982, Sing et al. 2002, and Juenger et al. 2011 have mentioned that in the case of activation by hemihydrate, the application of retarders might be necessary in order to prolong the setting times [99]. Vroomen 2007 used keratin and gelatine to retard the setting time of gypsum used for gypsum-stabilized earth and mentioned that gelatine has better

[30] Lootens, D., Jousset, P., Martinie, L., Rous- Sel, N., Flatt, R. J. Yield stress during setting of cement pastes from penetration tests. Cement Concrete Research, 39 (2009) 401 – 408.

[31] Struble, L. J., Lei, W. G. Rheological changes asso- ciated with setting of cement paste. Advanced Cement Based Materials, 2 (1995) 224 – 230.

[32] Zhang, J., Weissinger, E. A., Peethamparan, S., Scherer, G. W. Early hydration and setting of oil well cement. Cement Concrete Research 40 (2010) 1023 – 1033.

results. Also, citric acid [100] is used to retard the setting of gypsum. Prolonging of the setting time may be useful,

- to keep the mix workable for a time [14] and, therefore, to gain more time for transportation of the wet mix.
- to increase the pozzolanicity of the mixture through preventing gypsum to hydrate except from joining to the pozzolanic reactions.

Kusbiantoro et al. 2013 [101] used 1,5 to 2,5% citric acid as a natural based admixture for fly ash. Acartürk et al. 2018 [102] used 0,25 to 3% citric acid to retard the setting time of Calcium Sulfoaluminate Cements. Hence, in this study 0-2 wt% citric acid was used. Earth mixtures were prepared with various citric acid content and additives, and the VICAT test was applied on these mixtures to investigate its effect on setting of mix-design with proposed additives.

3.2.2.5 Bulk density

Density is largely a function of the constituent material's characteristics. Guettala et al. 2016 stated that even compressive strength is controlled by density [103]. To determine the relationship between strength performance and the density of the SES, bulk densities were determined. Moreover, bulk densities were used to determine the porosity of the stabilized earth specimens. The calculation was conducted with Micromeritics GeoPyc 1360 DryFlo-Pycnometer (see appendix G). All the specimens were dried in oven at 83 °C temperatures for 24 hours before testing.

3.2.2.6 Porosity

The quantity and long-term development of colloidal products such as ettringite or C-S-H influences the total porosity and affects strength and volume stability. The minimization of pores is obviously beneficial to strength in construction materials in general (Benavente et al., 2004; Molina et al., 2011) [104].

To calculate the porosity of specimens a final density calculation was necessary. This calculation was done with Micromeritics AccuPyc 1330 He-Pycnometer (see appendix G).

All the specimens were ground to a grain size of max. 60µm and the powders were dried in an oven at 83 °C temperatures for 24 hours before testing. After cooling down to the ambient temperature, the samples were prepared for testing.

3.2.2.7 Water insertion

Kafescioğlu et al., Işık et al., and Pekmezci et al. refer to using a water insertion test for the determination of the water resistance of stabilized earth specimens. Hence, in this study this test was conducted to determine the water resistance of earth with proposed admixtures. The water insertion was carried out according to the standard DIN 18945. However, the size of specimens used for the test was not that which was defined in DIN 18945 but 160x40x40 mm SES were used. DIN-EN-196-1 steel moulds were used for preparation of the specimens. Three totally different mix-designs were tested, and the specimens were cured at laboratory conditions (23°C and 50% relative humidity) for 14 days. The loss of material was determined by filtering the residue in the dip tank as defined in DIN. The experimental setting can be seen in Appendix I.

3.2.2.8 Capillary absorption

Capillary absorption was tested on 160x40x40 mm SES. The specimens were coated with paraffin, cross sections were prepared, and then weight and water level changes were determined. To avoid misleading results due to weight change, capillary water absorption was evaluated with water rise levels. Levels were marked every 1 mm of the samples and the time for water to reach each height was recorded. For the experimental setting, ASTM (Standard Test Method for Measurement of Rate of Absorption of Water by Hydraulic-Cement Concretes) C1585 [105] was used. The water rise according to time was recorded as described in ASTM. For further information and experimental setup see Appendix J.

3.2.2.9 Freeze-thaw cycle

In the laboratory, durability can be evaluated in numerous ways, such as soaking combined with strength test and cyclic freeze-thaw test [106] [51]. Freeze-thaw test was used to simulate extreme conditions in order to determine its durability. Researchers (Maher et al. 2003; Al- Tabbaa and Evans 1998; Makusa 2012) stated that, stabilized soils cannot withstand freeze-thaw cycles [107] and damage caused by freeze-thaw cycles (FTC) can take several forms. According to Yarbasi et al. 2007, Aldaood et al. 2013, and Strypsteen et al. 2017, the most common side effects are cracking and chipping of the material [108].

The stabilized earth specimens (SES) were subjected to freeze-thaw conditions in order to determine their durability under extreme conditions. In total, 9 specimens based on 3 different mix-design series were cast to use for the FTC test. The test has been conducted in accordance with the DIN 18945:2013-08. However, the size of specimens was not those in DIN 18945 but rather 160x40x40 mm SES were used. The specimens were cured at laboratory conditions (23°C and 50% relative humidity) for 14 days. The program called Celsius[33] was used to set the tempering cycle applied for the FTC test.

[33] It is a tempering file program offered by the manufacturer of the clime chamber

3.2.2.10 Delayed ettringite formation

Delayed ettringite formation (DEF) may be defined as the formation of ettringite in a cementitious material by a process that begins after hardening is substantially complete [109] and is a type of internal sulfate attack [110] causing damage in soil structures through mineral expansion during precipitation [111] and reduction in strength performance. There are no standard to assess the potential for DEF in laboratory samples [112]. One of the first tests to be extensively used was Duggan[34] test, however this test procedure has been progressively abandoned and new, improved tests like Fu Method and Kelham method have been developed [112]. Hence, in this study, the Fu method was applied by conduction of the DEF test. Fu test uses a specimen size of 25x25x10 mm [113]. In this study, however, a 160x40x40 mm specimen size was used. The DEF test procedure with further adaptions can be seen in Appendix L.

To investigate the observable sulphate attack, 9 specimens in total based on 3 different mix-design series were cast for saturation test. The specimens were firstly cured at laboratory conditions (23°C and 50% relative humidity) for 14 days. The length of specimens was recorded before the zero-day measurement. After that the specimens were placed into the tank for water suction. Zero-day measurement was done after 6 hours of water suction. Following this, specimens were dried in the climate chamber (see Figure 105 under Appendix K) at 85°C for 24h, cooled down to room temperature and then placed into the tank with saturated lime water for 56 days. The length of the specimens was measured every 7 days. For the measurements Mitutoyo ABSOLUTE Digimatic 12,7 mm 543-400B Serie 543 was used (see appendix E).

3.2.2.11 Thermal conductivity

Earth buildings perform also very well hydrothermally thanks to their relatively low thermal conductivity, large thermal mass and strong "breathability" (easy water/vapor phase change and transport) (Melia et al. 2014) [114] [14]. To investigate the effect of proposed stabilizers on the thermal conductivity of the stabilized earth, the thermal conductivity test was conducted, which is classified as a performance test. Thermal conductivity was determined by a thermal properties analyzer (Decagon KD2 Pro) with sensor TR-1 (see appendix M). Sensor TR-1 measures a range of 0.10 to 4 $WM^{-1}.K^{-1}$ with a ± 10% accuracy between 0.2 and 0.4 W $WM^{-1}.K^{-1}$ and ± 0.03 $WM^{-1}.K^{-1}$ [115]. The test was conducted on 160x40x40 mm SES. The

[34] Duggan involved the DEF test procedure

specimens were firstly cured at laboratory conditions at 23°C and 50% relative humidity for 14 days.

3.2.2.12 CO_2-emissions

One of the targets of this study is to develop a stabilized earth mixture, which causes less environmental impact than an earth mixture with cement addition. A CO_2-emission calculation was done, to prove that the earth stabilization with proposed admixtures causes less CO_2-emission. For this purpose, the mix-design with the best performance based on experimental tests was used as reference. The CO_2 emitting additives of the proposed stabilization was replaced with an equal amount of Portland cement. The performance results together with the related CO_2-emissions were compared with one other.

3.3 Materials

The experimental equipment used in this study has been documented and described in the appendix. The raw materials that have been used in this study are earth, natural pozzolan (trass), gypsum, lime, and cement. Earth was made by using clay (terrasol) and standardized sand that are available on the market. Hemihydrate gypsum, lime, and Portland cement type CEM I 32.5R were supplied from Switzerland. Trass was sourced however, from Germany. The other material used to moist the mixed materials was tap water supplied by the laboratory. The raw materials used for the preparation of samples as well as the variables in the raw mix are given in Table 5 and also shown in Figure 6.

Table 5: The raw materials used for sample preparation

Experimental Materials			
Item	**type**	**availability**	**Effect/means**
clay	mineral	recently industrialized product	binder
sand	granular material	industrialized product	compaction
trass	cementitious mineral	industrialized product	chemical
gypsum	hydraulic mineral	industrialized product	chemical
lime	hydraulic mineral	industrialized product	chemical
cement	cementitious mineral	industrialized product	chemical

Figure 6: The materials used by experimental programme

In the following chapters the additives and the earth used for stabilization are described in detail.

3.3.1 Additives used for stabilization

Among a variety of additives mentioned in chapter 2.4.3 trass, gypsum and lime were used as additives. Moreover, as given in Table 3 since lime and gypsum are traditional additives and since then significant experience has been collected on stabilization with these additives. In this study, the fly ash, which is a by-product and classified as an artificial pozzolan, is being substituted with a natural pozzolan called trass.

The content of stabilizing additives in total mix-design was always kept as 20,4 wt% of the total dry mix (additives + sand + clay).

3.3.1.1 Pozzolan and dosage

Trass[35] is a natural pozzolanic material, which can be found in various regions of the earth. The mineral composition of trass is mainly volcanic glass, zeolitized to a different extent (clinoptilolite), and secondary components from cyrstaloclasts of magnetite, zircron, apatite, biotite, quartz, sanidine, plagioclase [116].

In this study the Tubag trass (Germany) was used. It is also known as “rheinischer Trass”. Its chemical composition, obtained through X-ray fluorescence spectrometry (XRF), is given in Table 6.

Table 6: Chemical composition of the trass studied by X-ray fluorescence analysis. Values are given in mass % [117].

Component	SiO_2	Al_2O_3	TiO_2	Fe_2O_3	MgO	Mn_2O_3	P_2O_5	CaO	SO_3	K2O	Na_2O
(%)	56.90	18.50	1.10	6.30	2.20	0.2	0.2	5.20	0.20	5.70	3.50

Moreover, the X-Ray diffraction pattern of the trass can be seen in Figure 7.

[35] The name "Trass" is borrowed from Dutch "Tyrass" (Tarras) = putty (binding agent) and describes a product of the Vulcan Eifel made from tuff stone (also called duck stone)[161]

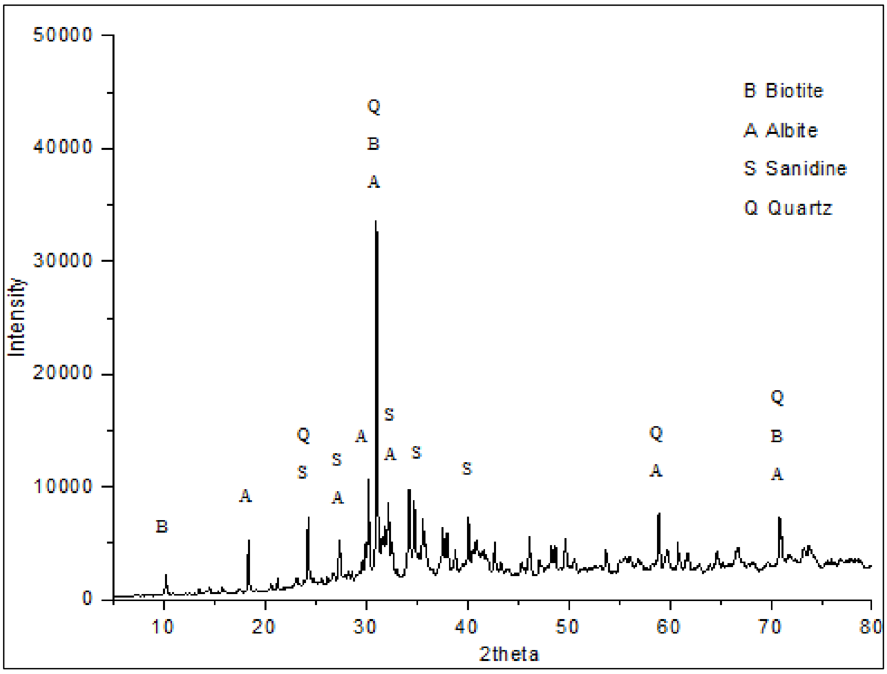

Figure 7: X-ray diffraction spectrum of the trass used in this study.

In addition, Figure 8 shows the trass in the Ternary diagram[36].

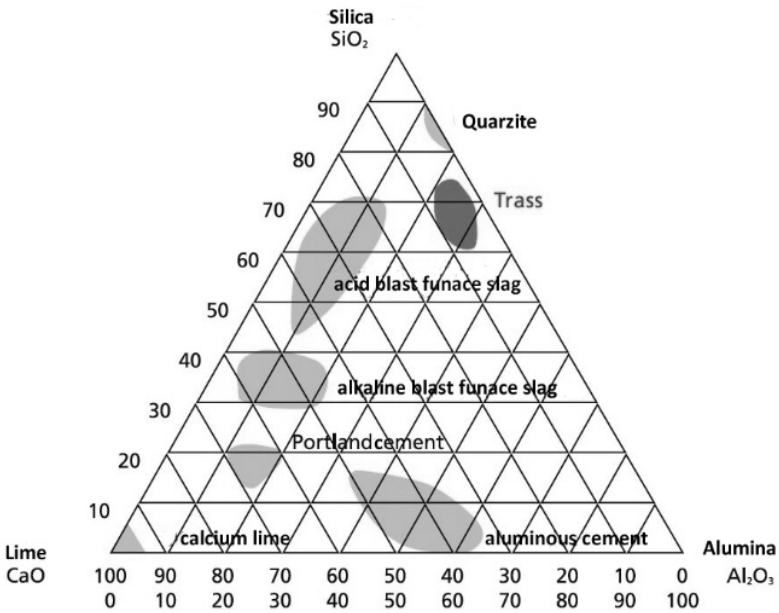

Figure 8: Ternary diagram of tubagTrass [117].

[36] Ternary diagrams represent three-component systems and are conveniently presented as triangular diagrams where each side corresponds to an individual binary system. Online: https://www.sciencedirect.com/topics/engineering/ternary-diagram (accessed April 28th, 2021)

The amount of trass used by preparation of stabilized earth specimens varies between 0 wt% to 20,5 wt%. The proportioning of trass to the total dry mix was done by weight and not by volume.

3.3.1.2 Gypsum and dosage

In this study, a commercially available hemihydrate gypsum ($CaSO_4 \cdot 1/2H_2O$) was used.
Several researchers used different percentages and types of gypsum in their research. Matalucci 1962 0-12%, Vroomen 2007 5 -30%, İslam et al. 2010 0-13%, Lopez et al. 2011 10% hemihydrate gypsum, Pekmezci et al. 2012 10%, Amin 2013 used 5-25% semi-hydrate gypsum. According to research of Işık[37] and Kafescioğlu[38] on the stabilization of earth with gypsum and lime, 10% of gypsum is enough for gypsum stabilization.
Moreover, according to Roesyanto et al. 2018, gypsum has better properties than organic additives because it does not cause air pollution, relatively cheap, fire resistant, and resistant to deterioration by biological factors and chemicals [118].

The amount of gypsum used by preparation of specimens varies between 0 wt% to 18 wt%. Proportioning of gypsum to the total dry mix was done by weight and not by volume.

3.3.1.3 Lime and dosage

A commercially available hydrated lime ($Ca(OH)_2$) was used in the investigation and in its processed form as was available from the package supplied by the manufacturer.

Wild et al. 1995 stated that generally 1-3% of lime addition is enough for modifying the soil properties. The research done on lime-stabilized earth have shown that a percentage of lime addition between 2-5% is an optimum amount. For instance, Kafescioğlu 2017, Pekmezci et al., Işık et al., and Vroomen 2007 suggested a lime content of 2-2,5% [119] [80] [61] [62]. Lopez et al. used 2% of lime addition [71].

Therefore, 2,5% wt% was used as reference. However, the amount of lime used in this study varied between 0 to 4,5 wt%. Proportioning of lime to the total dry mix was done by weight and not by volume.

[37] Işık, B. Conformity of Gypsum Stabilized Earth- Alker Construction with 'Disaster Code 97' in Turkey.

[38] Kafescioglu, R. Cagdaş bir Yapı Malzemesi Toprak ve Alker 2017

3.3.1.4 Water and dosage

The tap water supplied for laboratorial uses was used for all specimen preparations. The water content of a given earth for building purposes depends on the type of material and building element.

Water is not an additive in the proper sense, but the quality of the water usually added for processing plays a significant role in the properties of clay. The pH value is above all most essential. It can be said that any major deviation of the mixing water from the neutral pH value (about 7) adversely affects the strength properties or the water absorption of the clay minerals [1]. Water activates the binding forces of loam[39] [48]. In addition, water is necessary for the pozzolanic reactions. A lack of water has a negative effect on pozzolanicity.

In this study 16 wt%, 20 wt%, 25 wt%, 35 wt% and 45 wt% water was used in preparation of various specimens for tests. Proportioning of water to the total dry mix was done by weight and not by volume.

3.3.1.5 Saturated lime water and dosage

The saturated limewater was made by dissolving hydrated lime ($Ca(OH)_2$) powder into tap water. The water was then left to stand for 24 hours. The solution was finally carefully filtered so that no residues were present in the solution. The saturated limewater has different properties compared to tap water as shown in Table 7 [120].

Table 7: Comparison of properties of water and saturated limewater [120].

Water	Density	pH
Pot water	0.9909	8.5
Saturated limewater	0.9917	11.0

3.3.1.6 NaOH and dosage

The solubility of $Ca(OH)_2$ varies between 0,165 – 0,185 g/100mlwater [121] [122]. The value of solubility of $Ca(OH)_2$ taken in to account was 0,173 g/100mlwater [123] in this study. The dosage of NaOH was equal to the total amount of (OH^-) ions dissolved in 100 ml water.

3.3.2 Earth used for stabilization

The selection of earth or the knowledge about the mineralogy of the earth is a decisive parameter in earth stabilization. Specially because, a lack of knowledge about proper selection of binders and their interactions with soil minerals can lead to distress in structures due to the

[39] Loam is another definition used for clay. See also Glossary.

ineffectiveness of binders with time in soils containing high amounts of expansive minerals (Hausmann 1990; Chittoori and Puppala 2011) [73]. For instance, Kafescioğlu states that a marly earth should better be stabilized with cement addition, as it contains more than 50% calcium carbonate [119].

Another especially important fact is that the earth is extremely variable in terms of clay content and clay mineralogy throughout the world. In this study the earth was made by using industrial components with the aim:

- to eliminate the vary laboured work of characterisation and determination of a soil whose origin is not known. This eliminates the problem based on the variability of the earth.
- to eliminate sieving, grounding, or any other optimization processes needful to make an "earth" from "soil". As described in chapter 2.3.1, earth is the soil, which is suitable for construction.
- to eliminate the uncertainties of experimental results

It consists of 30% commercially available clay material for plastering and of 70% standard sand CEN EN 196-1 as can be seen Figure 9.

Figure 9: Clay and standard sand used for preparation of earth

3.3.2.1 Clay

The clay was supplied from the company Stroba Naturbaustoffe Ag Switzerland[40]. However, this company imports the clay material from Kärlicher TON- und Schamottewerke Mannheim & Co. Kg[41] Germany. This material is delivered in 25kg big paper bags. The chemical analyse of the clay is given in Table 8.

[40] https://www.stroba-naturbaustoffe.ch/ (accessed April 28th, 2021)

[41] https://kts-kg.de/ (accessed April 28th, 2021)

Table 8: Chemical analyses of the clay (Kärlicher 2020)[42]

Component	SiO_2	Al_2O_3	TiO_2	Fe_2O_3	CaO	MgO	K_2O	Na_2O	GV
Mass (%), glowed	0.3	<0.2	1.1	9.1	21.3	2.3	24.8	1.2	0.4

Moreover, the sedimentation analyses of the clay provided by the manufacturer is given in Table 9. As can be seen from the table where 97% of the clay particles are <63µm, 75% of these particles are <2µm.

Table 9: Sedimentation analyses of the clay (Kärlicher 2020)

Grain size (µm)	<63	<40	<20	<10	<6	<2	<1	<0.5
Mass (%)	97,00	95,6	93,80	88,90	85,20	75,40	68,10	58,70

According to mineralogical analyses the clay consists of 30wt% kaolinite, 45wt% mica, 25wt% quartz. There is no montmorillonite and Fe-Ti minerals. Moreover, the technical specification of the clay is given in Table 10.

Table 10: Technical specification of the clay (Kärlicher 2020)

Dry shrinkage	5,6%
Mixing water	32%
Dry bending strength	6,4 N/mm^2
Sieve residue > 63 µm	3%

3.3.2.2 Sand

The sand is supplied by SNL[43] from France. CEN Standard sand (ISO standard sand) is a natural sand, which is siliceous, particularly in its finest fractions. It is clean and the particles are generally isometric and rounded in shape. It is dried, screened and prepared in a modern workshop which offers every guarantee in terms of quality and consistency (SNL 2020)[44]. The information about the grain size distribution of the sand alone can be supplied from the manufacturer and is given in Table 11. The grading, measured by sieving, complies with the requirements of EN 196-1 (§5) and of ISO 679: 2009 (§5). This standard sand is also conforming to ISO 679.

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[42] https://kts-kg.de/wp-content/uploads/2014/03/T-4007-Tonmehl-Terrasol-gelb.pdf (accessed April 28th, 2021)

[43] https://www.standard-sand.com/en/snl-2/ (accessed April 28th, 2021)

[44] https://www.standard-sand.com/en/standard-sand-cen-en-196-1-2/ (accessed April 28th, 2021)

Table 11: The grading of the sand according to manufacturer (SNL 2020)

Square mesh, size in mm	Cumulative (%), retained
0.08	99 ± 1
0.16	87 ±5
0.5	67±5
1.0	33±5
1.6	7±5
2.0	0

The clay part contains 97% of fine particles (<63µm) (see Table 9) including clays and silt. The X-ray powder diffraction technique was revealed, thanks to Rietveld methods [92], [55] that the main mineralogical components consist of techtosilicates (framework silicates); quartz (21,3 wt%) and phyllosilicates (sheet silicates); muscovite/illite (24,8 wt%), kaolinite (21,3 wt%) and smectite (16,6 wt%). The complete mineralogical composition is given in Table 12.

Table 12: Chemical composition of terrasol used for mix-design and specimens

Component	Anastase	Calcite	Chlorite	Goethite	Kaolinite	Microcline	Muscovite/ Illite	Plagioclase-Albite	Pyrite	Quartz	Rutile	Smectite
(%)	0.3	<0.2	1.1	9.1	21.3	2.3	24.8	1.2	0.4	21.3	1.6	16.6

3.3.2.3 Is the selected clay suitable for constructional purposes?

As has been discussed in the chapter 2.3.1.4 clay minerals, the kaolinite and illite do not swell and crack and are therefore, appropriate for earth construction.

3.3.2.4 Is the designed earth suitable for constructional proposes?

According to Işık, an earth containing ca. 30% of clay is used for traditional earth constructions, however, earth with up to 10% clay content is suitable, for instance, in earth stabilization using gypsum and lime. In addition, according to the Table 1 given in chapter 2.3.2 Soil classification, the designed earth can be classified as fine-grained soil and, therefore, is suitable for earth construction.

3.3.3 Mix-design preparation for specimens

This chapter deals with the preparation of mix-design. The mix-design will then be used for the preparation of specimens to determine their physical properties.

3.3.3.1 Mixing process

Initially, trass, gypsum, and lime were mixed with earth according to the mix-design proportions. Proportioning of earth to the stabilizers as well as water was done by weight and not by volume. The dry mix was mixed with a Turbula® 3D shaker mixer for around 5 minutes. After the shaking process, the dry mix was moved into a container. The water was then added to the mixture. After adding water, the mixing process took no longer than 3 minutes. The water required for the mix should only be added at very end of the mixing process, after the very necessary dry mixing phase [44]. Finally, the mixture was cast into the steel moulds as shown in Appendix B.

3.3.3.2 Drying process

The drying process of all specimens took place in the laboratory. All specimens were kept under laboratory conditions of at 23°C and 50% relative humidity. The drying process differs from one week to four weeks, as described in different experiments.

4 Experimental results

This chapter includes the results of all the experimental tests described in the methodology. The tests have been carried out on stabilized and non-stabilized earth specimens with varying clay content, in order to determine both their physical properties and the stabilization effect.

4.1 Development tests (properties of stabilized earth)

4.1.1 Strength performance

To better identify the effects of different binders on the increase in strength, the strength performance tests were conducted in two steps:

a. Tests on stabilized sand specimens: binders were mixed with standard sand without clay content.
b. Tests on stabilized earth specimens: binders were mixed with earth consisting of 30% clay and 70% standard sand.

Furthermore, strength performance tests were used to observe the behaviour of pozzolanicity of various mix-designs. The pozzolanic reactivity can be activated with the help of different chemicals. In a study of Abdullah et al. 2012 it was stated that sulfate activation can be studied by using several chemicals such as gypsum, $CaSO_4 \cdot 2H_2O$ and sodium sulfate, Na_2SO_4, whereas NaOH and $Ca(OH)_2$ are used for alkali activation studies [124]. In this study, NaOH was used to further investigate the pozzolanicity of the mix-designs.

4.1.1.1 Stabilized specimens without clay

Standardized sand as described in 3.3.2.2, was used in the preparation of specimens. The clay content of the sand specimens was zero. As mentioned in the introduction of strength performance, firstly the stabilized sand specimens (SSS) were tested to investigate the stabilization effect of additives alone. To produce a mix-design suitable for casting, the water/binder(trass+gypsum+lime)/sand ratio was determined as 0,65/1/3. Although, it was planned to use ratio a 0,5/1/3, this ratio was not sufficient to prepare castable mix-designs. The addition of additives and water to sand was done in ratios by weight of the total dry mix. The trass and gypsum content were used in variations of 0 to 18%. Lime content was kept at 2,5%. However, additionally, saturated limewater (SLW) and NaOH were used instead of 2,5% lime to investigate the pozzolanicity of the mix-design.

Table 13 depicts the sample composition of mixtures used to cast the SSS. The specimens, which were prepared with SLW and NaOH instead of 2,5% of lime, are labelled in the related graphs.

Table 13: Labelling of stabilized sand specimens

Label-ling	0182,5	5132,5	1082,5 & T10G8	1262,5	1442,5 and T14G4	1622,5 & T16G2	1802,5
Descrip-tion	Sand with 18,5% gypsum, 2.5% lime	Sand with 5% trass, 13%gypsum, 2.5% lime	sand with 10% trass, 8%gypsum, 2.5% lime	Sand with 12% trass, 6%gypsum, 2.5% lime	sand with 14% trass, 4%gypsum, 2.5% lime	Sand with 16% trass, 2%gypsum, 2.5% lime	Sand with 18% trass, 2.5% lime

4.1.1.1.1 Flexural strength

The 7day and 28day results of FS tests are shown in Figure 10. As can be observed in the graph, for all specimens, FS improvement after 7 days shows similar behaviour. A remarkable improvement can be observed after 28 days. However, the FS improvement of the SSS is dominated with gypsum content in specimens. The higher the gypsum content is, the better the improvement in FS is.

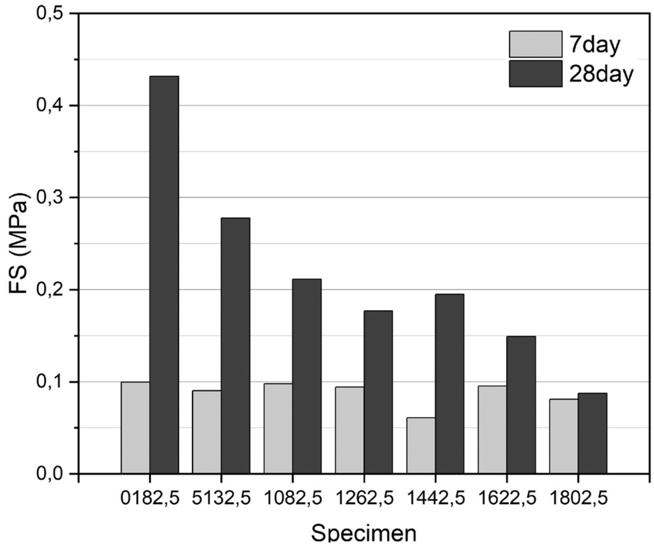

Figure 10: Flexural strength of SSS

As it can be observed in Figure 11, the FS of specimens after 7 days does not show a significant difference. But, after 28 days of curing time, the FS increases. The increase is, however, according to the graph, related to the increase of gypsum content. Therefore, it can be observed that specimens with higher gypsum content show better FS.

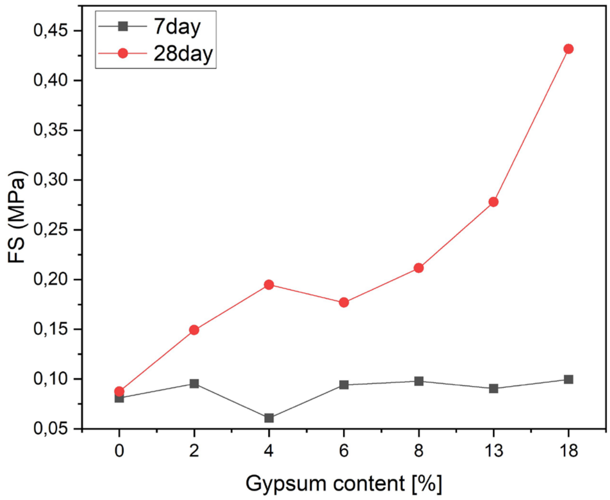

Figure 11: Relationship between flexural strength and gypsum content of SSS

As mentioned in chapter 3.3.1.3, in this research mainly, 2,5wt% of lime content was used as a reference at the recommendation of the researchers. However, the pozzolanicity of the mix-designs were investigated using SLW and NaOH. Results were compared with the lime content, which was set as a reference.

SLW was mixed with 3 different mix-design series to investigate the pozzolanicity. The 7day and 28day FS results of SSS with SLW are plotted in Figure 12. According to results, the specimen T16G2 presents the highest improvement in strength from 7 to 28 days. T0G8 lost strength from 7 to 28 days. A significant improvement of FS from 7 to 28 days was not observed.

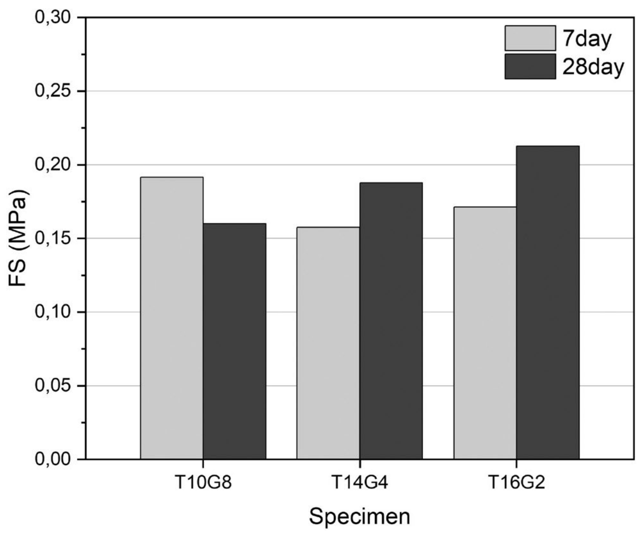

Figure 12: Comparison of 7day and 28day flexural strength of SSS with SLW

A comparison of 7day FS of specimens with SLW and 2,5% of lime can be seen in Figure 13. Compared to 2,5% lime addition, SLW significantly contributes to the development of the FS of mix-designs after 7 days.

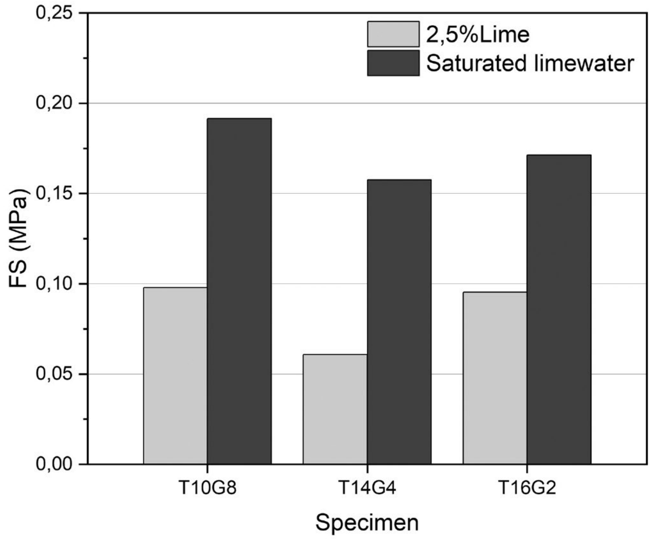

Figure 13: Comparison of 7day flexural strength of SSS with SLW and 2,5% lime

Moreover, a comparison of 28day FS of specimens with SLW and 2,5% of lime is presented in Figure 14. The results present that, only T16G2 showed a remarkable improvement of FS by adding SLW when compared to 2,5% of lime addition.

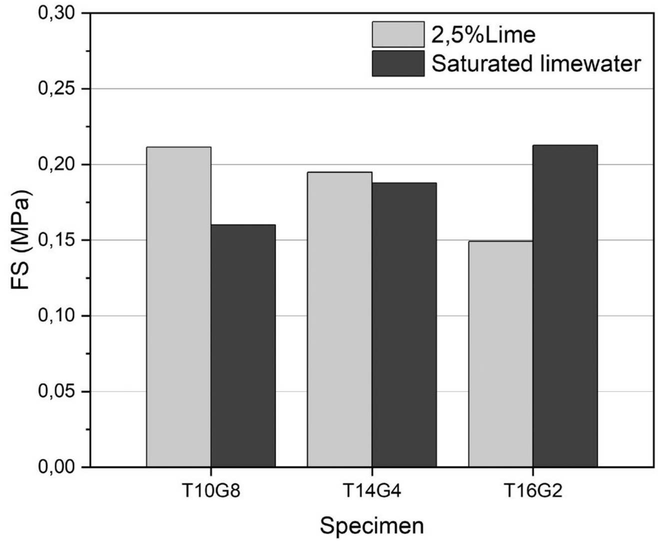

Figure 14: Comparison of 28day flexural strength of SSS with SLW and 2,5% lime

4.1.1.1.2 Compressive strength

As mentioned in the previous chapter, after the flexion test, each specimen was divided into two prismatic parts. These parts were used to determine the CS. The results of both 7day and 28day CS are plotted in Figure 15.

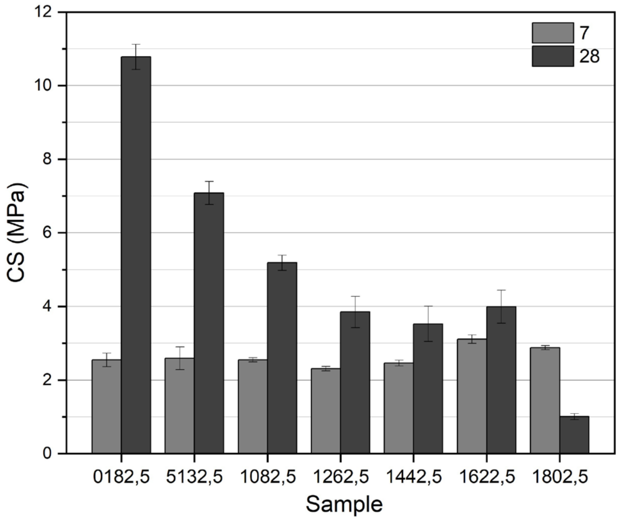

Figure 15: Compressive strength of SSS with various mix-designs

As it can be observed in Figure 15, the CS of specimens after 7 days does not show a significant difference. But, after 28 days of curing time, the CS does, in fact, increase. However, according to the graph, as with the FS results, the increase is related to the increase of gypsum content. Therefore, it can be observed that the specimens with higher gypsum content show better CS.

The 7day and 28day CS results of SSS with SLW are plotted in Figure 16. According to the results, T16G2 presents the highest strength both after 7 and 28 days, and the increase of strength from 7 to 28days is higher in comparison to other specimens.

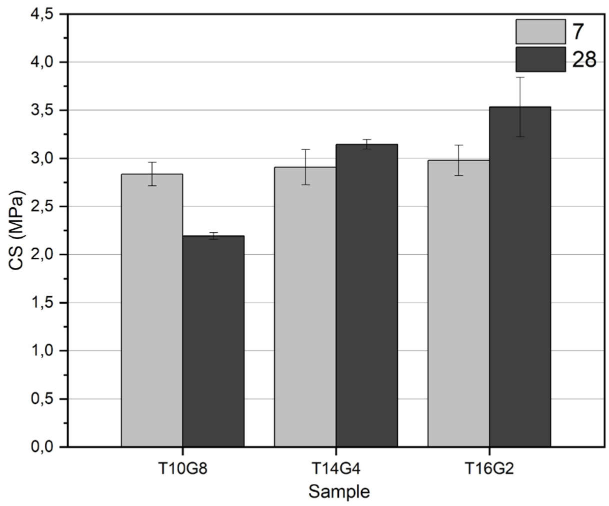

Figure 16: Compressive strength of SSS with saturated lime water

Figure 17 presents the comparison of 7day CS of SSS with 2,5% lime addition and SSS with SLW. As can be seen in the graph, the SLW has only slightly improved the CS of specimens T10G8 and T14G4.

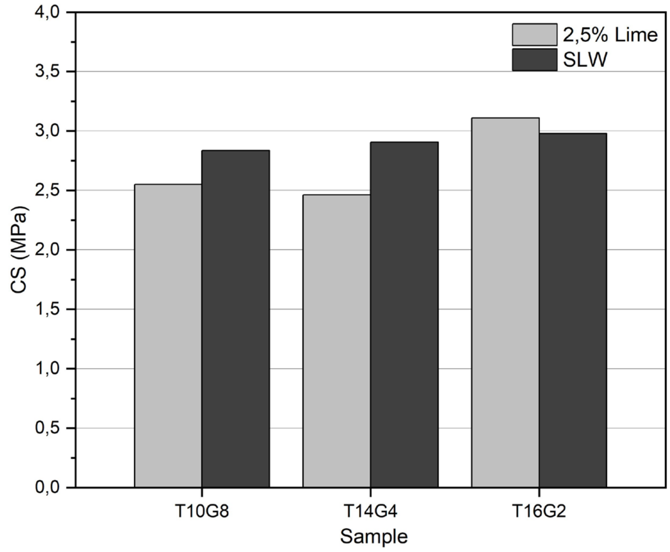

Figure 17: Comparison of 7day compressive strength of SSS with SLW and 2,5% lime

Figure 18 presents the comparison of 28day CS of SSS with 2,5% lime addition and SSS with SLW. While the addition of SLW has dramatically reduced the CS of T10G8, the specimens T14G4 and T16G2 have minimally lost CS compared to SSS with 2,5% of lime addition.

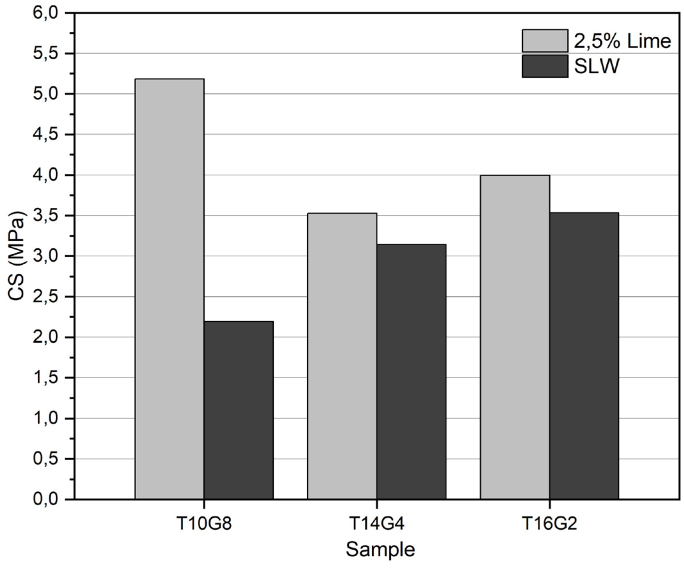

Figure 18: Comparison of 28day compressive strength of SSS with SLW and 2,5% lime

Moreover, the pozzolanicity was further investigated with the addition of NaOH. For this purpose, the T10G8 (10 wt% trass + 8 wt% gypsum) mix-design was used as reference. The FS results of SSS with 2,5 wt% of lime, SLW, and NaOH equal to moll of OH^- ions in one litter of SLW, are plotted in Figure 19.

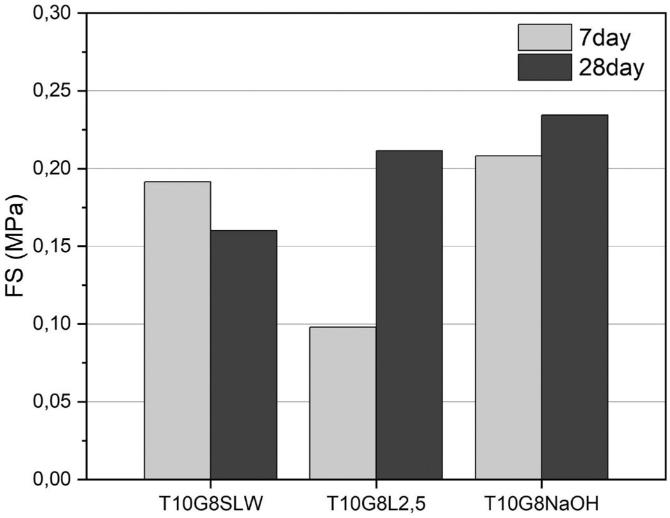

Figure 19: Comparison of flexural strength of SSS with 2,5% lime, saturated lime water and NAOH

The specimen T10G8NaOH presents the highest FS both after both 7 and 28 days. While T10G8NaOH and T10G8L2,5 present an increase of FS from 7 to 28 days, the addition NaOH negatively effects the FS of T10G8SLW.

The CS results of the same specimens are shown in Figure 20 below. In contrary to FS results, the highest CS was observed by T10G8L2,5. The increase of CS of T10G8NaOH and T10G8L2,5 from 7 to 28 days is remarkable. On the other hand, as we can observe in the FS results, the specimens with SLW (108SLW) lost CS from 7 to 28 days and present the lowest CS after 28 days.

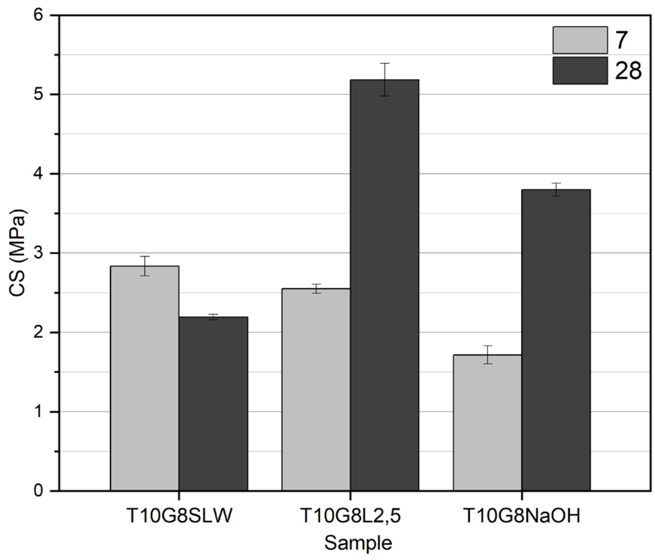

Figure 20: Compressive strength of SSS with SLW, 2,5wt% lime and 2,5% NaOH

4.1.1.1.3 Summary of chapter

The results have shown that the FS and CS of the specimens containing 18% and 13% gypsum are dominated by the high gypsum content, in other words by hydration of gypsum. This has also been proved through X-Ray diffraction analyses as can be seen in chapter 4.1.2. Although SSS with SLW when compared with each other, showed an increase of FS and CS from 7 to 28 days, SLW compared to 2,5% of lime addition (reference lime content used in this study) could neither significantly contribute the improvement of FS nor CS. Furthermore, the results showed that NaOH improved the FS of the specimens but not the CS.

4.1.1.1 Stabilized earth specimens (specimens with sand and clay)

The compressive strength (CS) and flexural strength (FS) results of stabilized sand specimens have shown that the strength performance of specimens with high gypsum content is mainly determined by the hydrated gypsum and much less by the pozzolanic reaction. For this reason, further strength performance tests on stabilized earth specimens (SES) were conducted with 3 mix design combinations, respectively T10G8L2,5 (10% trass, 8% gypsum and 2,5% lime), T14G4L2,5 (14% trass, 4% gypsum and 2,5% lime) and T16G2L2,5 (16% trass, 2% gypsum and 2,5% lime).

The earth used for the preparation of the SES consists of 30% clay and 70% standardized sand as described in chapter 3.3.2. The samples were kept under laboratory conditions of at least 23°C temperature and 50% relative humidity and left to dry. The specimens were cast in a steel mould. For this purpose, 20% of water was enough to produce castable mixtures for each mix-design proportion.

4.1.1.1.1 Flexural strength

As with SSS, a series of beam specimens with dimensions of 160x40x40mm were prepared and tested to determine the FS. Table 14 tabulates the sample composition of mixtures used to manufacture SES.

Table 14: Labelling of stabilized earth specimens for FS and CS

Labelling	T10G8	T14G4	T16G2
Description	Earth with 10wt% trass, 8wt% of gypsum and 2.5wt% of lime	Earth with 14wt% trass, 4wt% of gypsum and 2.5wt% of lime	Earth with 16wt% trass, 2wt% of gypsum and 2.5wt% of lime

7 and 28-days results of FS tests are shown in Figure 21. As can be observed in the graph, T14G4 presents the higher FS after 7 days. However, while after 28 days T10G8 and T14G4 lost FS, the FS of T16G2 remarkably increased after 28 days. It is not clear why the specimens T10G8 and T14G4 lost FS from 7 to 28 days.

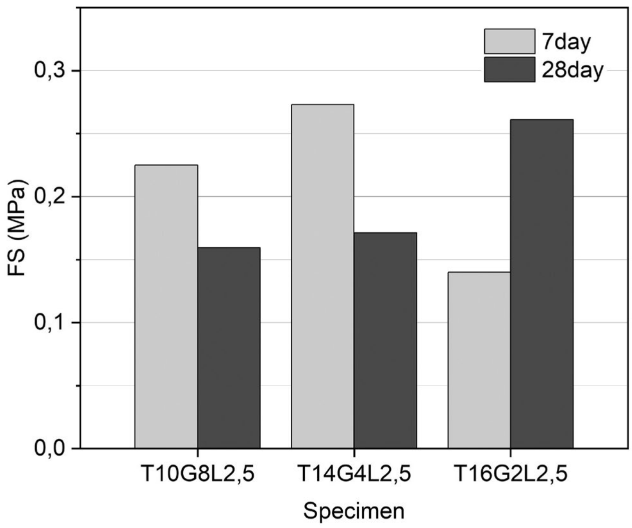

Figure 21: Flexural strength of SES

Figure 22 shows the development of FS versus gypsum content in the use of SLW.

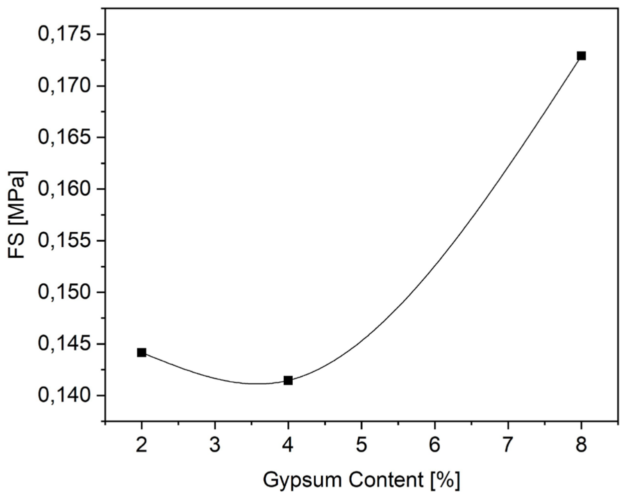

Figure 22: FS versus gypsum content of SES with SLW

4.1.1.1.1.1 Effect of water content

7day FS of SES versus water content is given in Figure 23. According to the results, the highest FS was reached with mix-design T16G2L2,5 with 16% water content. Although T10G8L2,5 contains the highest gypsum content, 16% of water may not be enough both for both the hydration of gypsum and pozzolanic reactions within this mix-design. However, when 20% of water is used T16G2L2,5 shows the lowest FS level. While T14G4L2,5 shows constant behaviour, T10G8L2,5 gains more strength. With 25% water, the SP of T10G8L2,5 is higher than other mix-designs, which can be as expected due to better hydration of the gypsum.

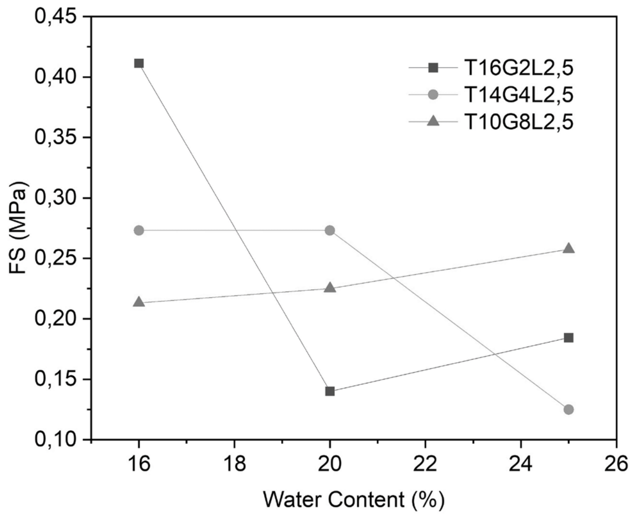

Figure 23: 7day FS of SES with different water content

Moreover, 28day FS of SES versus water content has been plotted in Figure 24. The SP of T16G2L2,5 and T14G4L2,5 shows a parallel behaviour, and it decreases with the increase of water content. Although, a slight improvement can be observed, the FS of T10G8L2,5 also decreases.

It was observed that although the FS of T10G8L2,5 slightly increases from 16 to 20% water, the 25% water content caused a decrease in the FS of this mix-design.

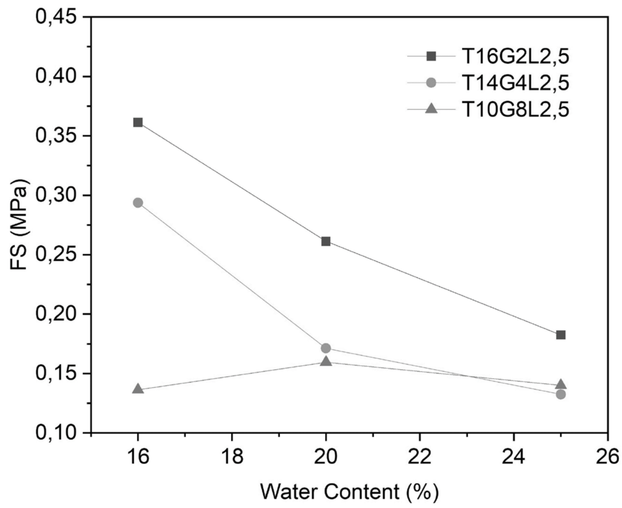

Figure 24: 28day FS of SES with different water content

Finally, increasing water content continuously contributes to the strength of T10G8L2,5 after 7 days. However, after 28 days, there may be less unhydrated gypsum in the mix-design so that 25% of water becomes insufficient to improve the strength of T10G8L2,5 (see Figure 25).

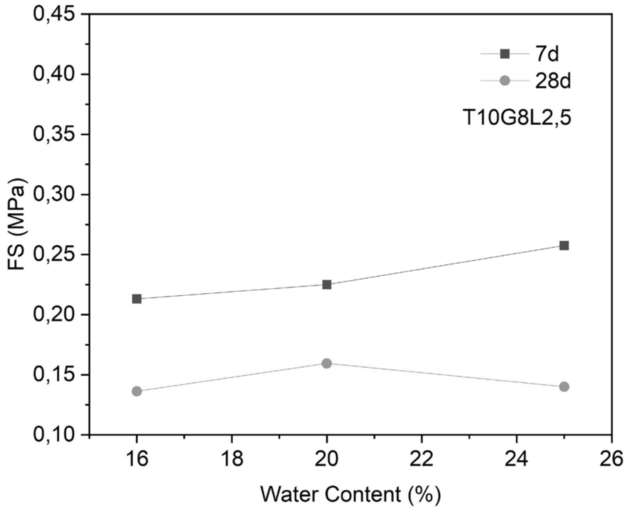

Figure 25: FS versus water content. T10G8L2,5

According to 7day results, when the water content is increased from 16 to 20%, the strength of T14G4L2,5 remains relatively constant. However, upon reaching 25% water, the FS of this mix-design dramatically decreases. It was noted however, that after 28 days, the increase in water content does not contribute to the strength of T14G4L2,5 (see Figure 26). With 25% of water, this mix-design reaches a stabile FS without the influence of curing time.

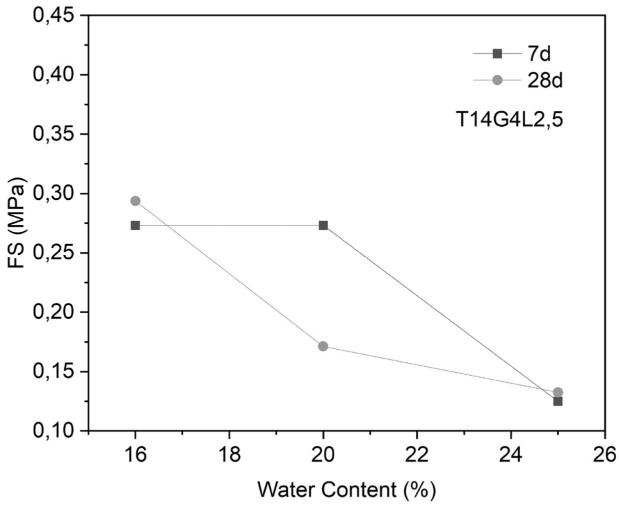

Figure 26: FS versus water content. T14G4L2,5

The effect of an increase in water content is more dramatic for mix-design T16G2L2,5. However, as with T14G4L2,5, with 25% of water, this mix-design reaches a stabile FS without the influence of curing time (see Figure 27).

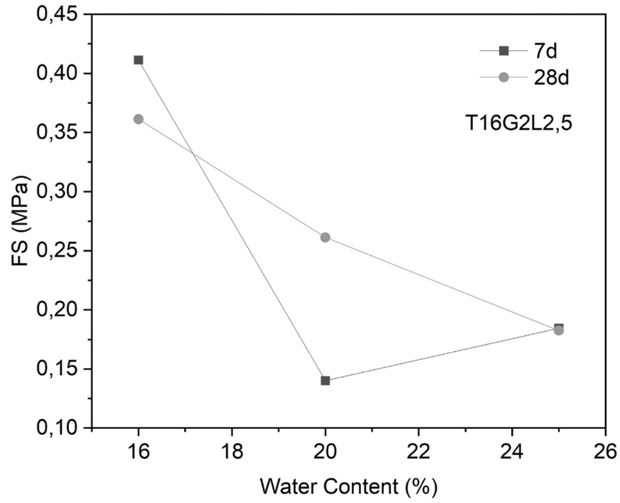

Figure 27: FS versus water content. T16G2L2,5.

4.1.1.1.1.2 Effect of wetting-drying

A comparison of FS of the SES in dry and wet condition is given in Figure 28. The wet CS of the plain earth could not be plotted as these specimens were immediately swelled and dissolved in water. Therefore, only the dry FS was given. T14G4L2,5 shows the highest FS in dry condition; T10G8L2,5 and T16G2L2,5 follow this respectively. However, in wet conditions, the increase of FS follows parallel to the increase of trass content in specimens. Therefore, T16G2L2,5 showed the highest strenght. Moreover, it can be observed that both wet and dry FS of this mix-design is very closed in comparison, which can be attributed to the by-products of the water-insoluble pozzolanic reaction.

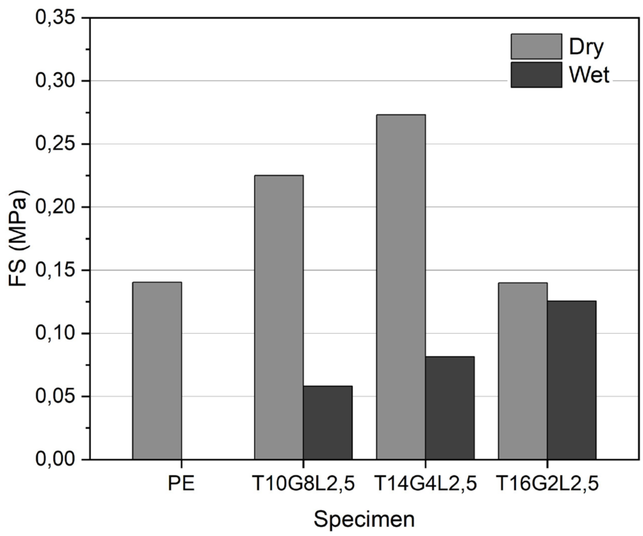

Figure 28: FS of SES in dry and wet conditions.

4.1.1.1.2 Compressive strength

7day and 28day compressive strength (CS) tests were carried out on prismatic specimens with dimensions of 160x40x40 mm.

The 7day and 28day results of CS tests of SES are shown in Figure 29. As can be seen in Figure 29, the maximum CS is obtained for T16G2 samples containing 16 wt% of trass and 2 wt% of gypsum. While T10G8 contains the highest amount of gypsum, it does not show an increase in CS from 7 to 28 days, the samples prepared with a higher amount of trass progressively gain strength from 7 to 28 days. Samples containing 14 and 16wt% of trass show parallel behaviours of strength improvement from 7 to 28 days. Using a higher content of trass allows the improving of the CS of stabilized earth.

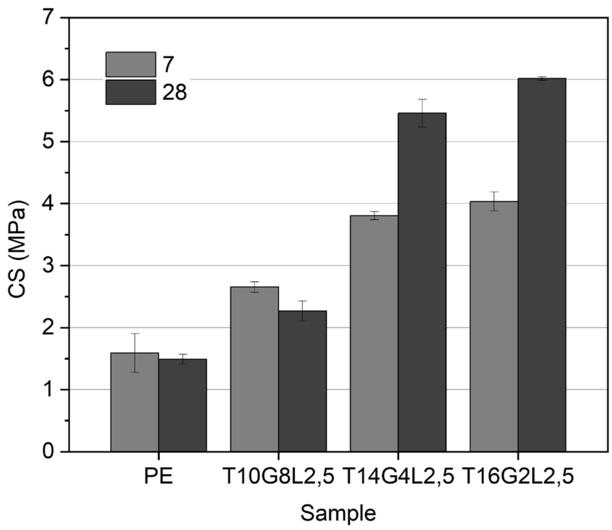

Figure 29: CS of the SES

4.1.1.1.2.1 Water content

A comparison of the effect of different water content on both 7day CS of SES and plain earth is given in Figure 30. All specimens including plain earth have lost CS with the increase of water content. The decrease in CS of the plain earth shows a linear behaviour in comparison to the SES. The nonlinear behaviour observed by SES may be attributed to pozzolanic reactions. As the water content increases, the SES tends to reach a closer CS value, which is ca. 50% lower than the CS of specimens with 16% water.

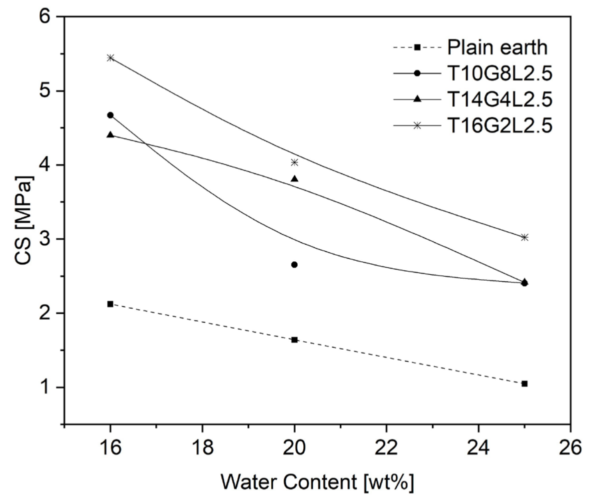

Figure 30: 7day CS versus water content

Furthermore, Figure 31 shows the effect of different water content on the 28day CS of SES and plain earth. As can be observed in the graph, all specimens, including plain earth, lost CS by the increase of water content. However, in comparison to 7day CS results, this time the CS of the SES showed a parallel nonlinear behaviour when compared to one another. On the other hand, as with the 7day results, the decrease in CS of the plain earth shows a linear behaviour in comparison to the SES.

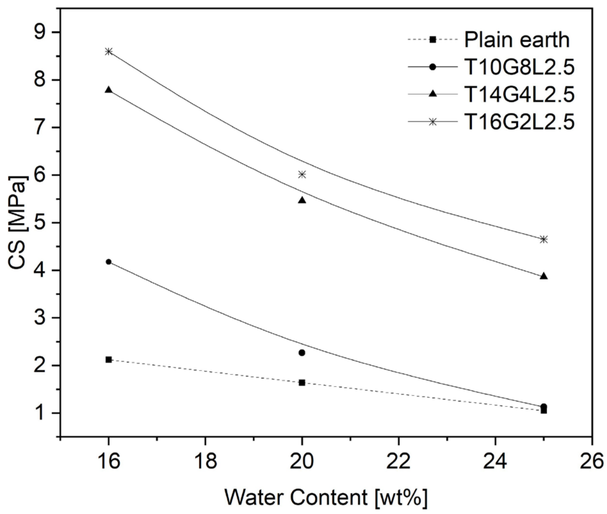

Figure 31: 28day CS versus water content

4.1.1.1.2.2 Clay content

The comparison of CS of SSS with 0% clay, SES with 30% of clay and clay specimens with 100% clay are given in Figure 32. For comparison, the mix-design T10G8L2,5 was used as a reference. All specimens were prepared with the sufficient water content necessary for casting, which was 16,3% for SSS, 20% for SES, and 45% for clay specimens. T10G8L2,5 without clay content showed better SP. Moreover, when 30% of clay was added, a loss of 43% of CS was observed. When sand content was replaced with 100% clay, the CS was improved by about 9%. This causes, however, 2,8 times more water consumption.

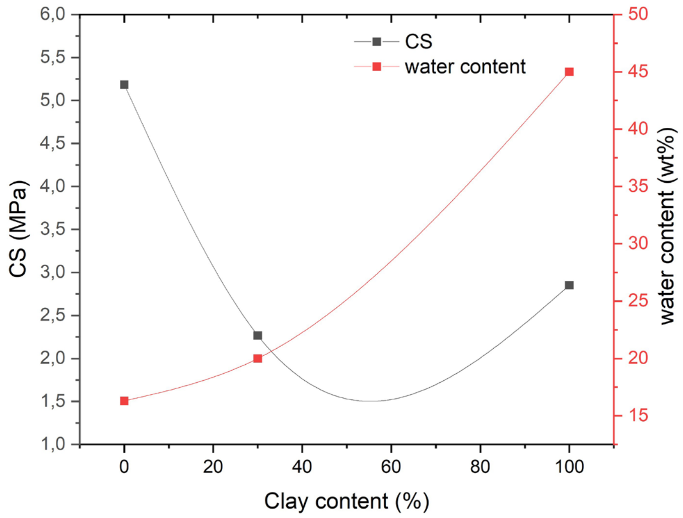

Figure 32: Effect of clay content on CS

Moreover, the T10G8L2,5 mix-design specimens with 100% clay have better SP with the related water contents than SES with 30% clay and their attributed water contents (see Figure 33). However, as mentioned in chapter 3.3.3.1, although 25% of water is enough for compacted specimens, a high amount of water is needed for the preparation of cast clay specimens.

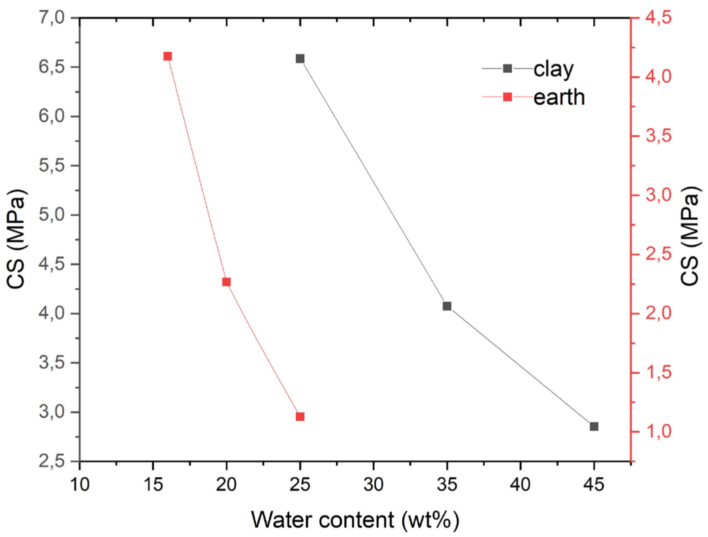

Figure 33: CS performance of SES and stabilized clay specimens with different wate contents

4.1.1.1.2.3 Effect of wetting-drying

For this purpose, a series of SES cured under laboratory conditions were first placed in water tank and completely immersed in water for 24 hours as shown in Figure 34.

Figure 34: SES in water tank after 24 hours

The specimens were then removed from the water tank. Whereas one part of the specimen bars were pressed directly after being removed from the tank, the other parts were again dried under laboratory conditions for 28 days and then pressed. CS results of wet and wetted-dried specimens are shown in Figure 35.

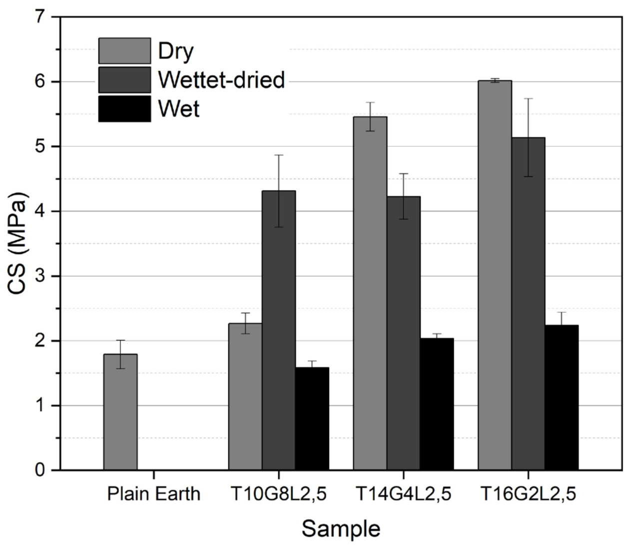

Figure 35: CS of SES with dry, wetted-dried, and wet conditions

According to these results, in the wet condition, the SES dramatically lose their strength. Reduction in CS under saturation condition can be attributed to the development of pore water pressure and the liquefaction of non-stabilized clay minerals in the brick matrix [67].

The trass/gypsum ratio of T10G8L2,5 T14G4L2,5 and T16G2L2,5 is respectively 1,25, 3,5 and 8 and it can be observed from the graph that there is a linear relation between CS and the trass/gypsum ratio, which can be attributed to the pozzolanicity of mix-designs. The results clearly present that the mix-design T16G2L2,5 possesses the highest SP in all conditions. In addition, when compared with T14G4L2,5 and T16G2L2,5, the mix-design T10G8L2,5 presents remarkable strength development from its dry to wettet-dried condition. This may be due to several reasons such as the unhydrated gypsum content remaining after casting, increased pozzolanicity or delayed ettringite formation caused by the presence of water.

4.1.1.1.2.4 Effect of saturated lime water

In this chapter, the effect of SLW on 7day CS of stabilized earth specimens (SES) was investigated. The SES have been produced with 16wt% of SLW as this amount of water was enough to cast the specimens. The preparation of SLW was described in chapter 3.3.1.5. As the content of stabilizing additives in total mix-design was always kept as 20,4 wt% of the total dry mix (additives + sand + clay), the dry lime content was filled with an equal amount of terrasol (2,5 wt%). T10G8 consumed the added water within 1-4 minutes due to the rapid hydration of gypsum. It was necessary to cast these specimens as quickly as possible, at maximum no later than 5 minutes and casting was done by compacting. However, T14G4 and T16G2 could not consume the water as rapidly as T10G8, so it was possible to create pourable casting.

The 7day CS results of SES with SLW are plotted in Figure 36. As can be seen in the graph, SLW has a dramatic effect on CS of the SES. T16G2 lost 2/3 of its strength in comparison to those specimens with 2,5% lime. Although T10G8 also lost 1/3 of its strength, the decrease of CS in these specimens is less than that observed in other specimens, which can be explained by the strength resulting from the hydration of gypsum.

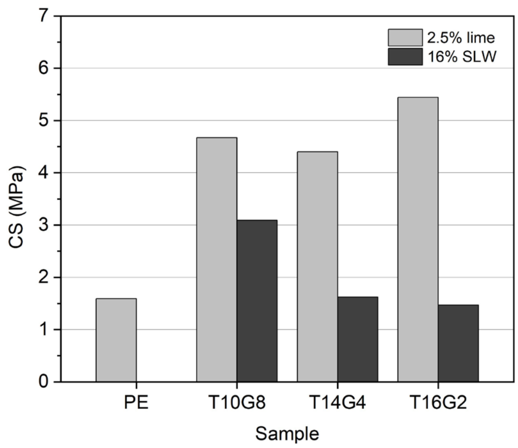

Figure 36: Effect of SLW on 7d CS of SES

In this experiment two observations were notable: Not using 2,5% of lime caused a rapid setting of T10G8 and made it possible to cast the specimens with a 16% water addition.

4.1.1.1.2.5 Cement and different amount of lime

In this experiment the mix-design T16G2L2,5, which showed the best CS performance as plotted in Figure 29 was used as a reference. The amount of lime (2,5%) and gypsum (2%) was then replaced with 4,5% cement to compare the performance of TGL stabilization with cement stabilization. Table 15 depicts the sample composition of mixtures with varying lime content and 4,5% of the cement used for the CS test.

Table 15: Labelling of SES with cement and different lime content

Labelling	T16G2L2,5	T16G3L1,5	T16L4,5	T16C4,5
Description	Earth with 16wt% trass, 3wt% of gypsum, 1,5wt% of lime	Earth with 16wt% trass, 3wt% of gypsum, 1,5wt% of lime	Earth with 16wt% trass, 4,5wt% of lime	Earth with 16wt% trass, 4,5wt% of cement

The 28day CS results are given in Figure 37. As the results show, the specimen T16L4,5, which contains 0% of gypsum showed, with 1,85MPa, the lowest strength. Also, where T16G3L1,5 showed 4,64 MPa, the specimen T16C4,5, which contains 4,5% cement showed a strength of 2,48 MPa.

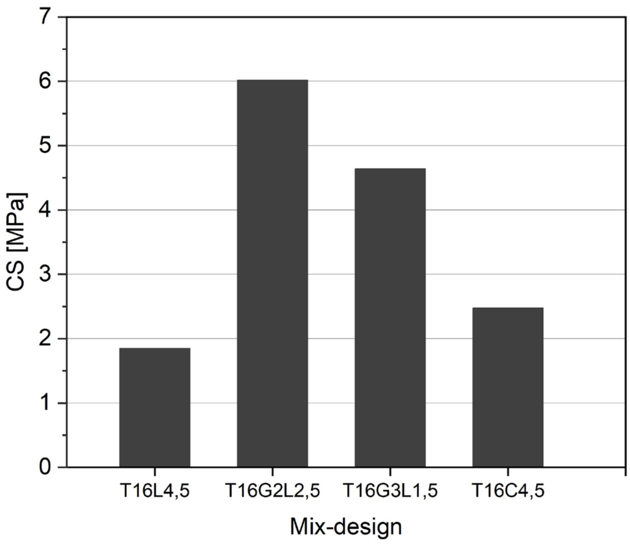

Figure 37: CS of SES with different lime content and cement

4.1.1.1.2.6 Failure modes of stabilized earth specimens

Predicting resulting failure modes is very essential [125] in the construction design. Various stabilized mix-design specimens were analysed to document the failure modes.

This result shows that mixing is a significant parameter as this ensures a homogenous distribution of both clay particles and the minerals of the additives. As can be seen in Figure 38a, in non-homogenous mixtures, the flocculated lime and/or gypsum particles have been identified in the sample pieces after compression. The stabilized clay specimens as demonstrated in Figure 38b and stabilized earth specimens as shown in Figure 38c presented similar failure modes as the concrete samples described in DIN-EN 12390.

Figure 38: Failure modes of SES. 38a, insufficiently mixed SES. 38b, stabilized clay specimen. 38c, sufficiently mixed SES

4.1.1.2 Summary of strength performance tests

Strength performance (SP) tests were firstly applied to stabilized sand specimens (SSS) without clay (0%) content. It is known that when water is added to gypsum it hydrates and when water is added to pozzolan and lime they react together, called a pozzolanic reaction. SSS enabled the better documentation of the performance of additives alone (trass+gypsum+lime). While 7day cured specimens showed almost a parallel SP varying between 2-2,8 MPa, however, after 28 days of curing SP of SSS was dramatically dominated by gypsum content and reached up to ca. 11 MPa. Whereas specimens with only gypsum and lime content showed the highest strength, specimens with only trass and lime content showed the lowest strength. Due to the dominant effect of gypsum on strength characteristics of stabilization, the mix-designs labelled with 182,5, 5132,5 were not further used by earth specimens. Also, 1262,5 showed a remarkably similar strength character to 1442,5 and 1802,5 showed a very weak SP. These mix-design combinations were also abandoned by tests with SES.

When the clay is present in specimens, SP gains a pozzolanic characteristic. As the graph below demonstrates, in earth specimens the strength value improves while gypsum content decreases. This can be attributed to the improved pozzolanicity, which the presence of clay minerals contributes to the pozzolanic reactions. Experiments on SES have shown that when the trass/gypsum ratio is increased while keeping lime content at 2,5% (as a reference value), the strength of stabilized earth increases significantly.

As can be seen in Figure 39 and Figure 40, the SP of earth specimens increases both after 7 days and 28 days. On the contrary, SSS presents loss of strength until a trass/gypsum ratio of 3.5 at which point the strength again increases.

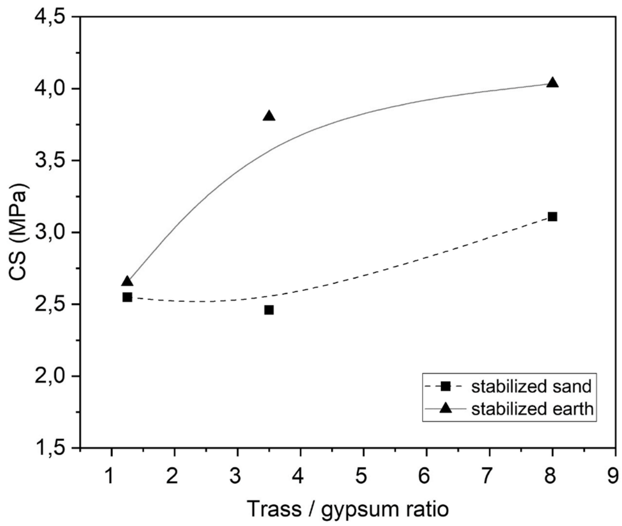

Figure 39: 7day CS versus trass/gypsum ratio. Comparison of SES with SSS.

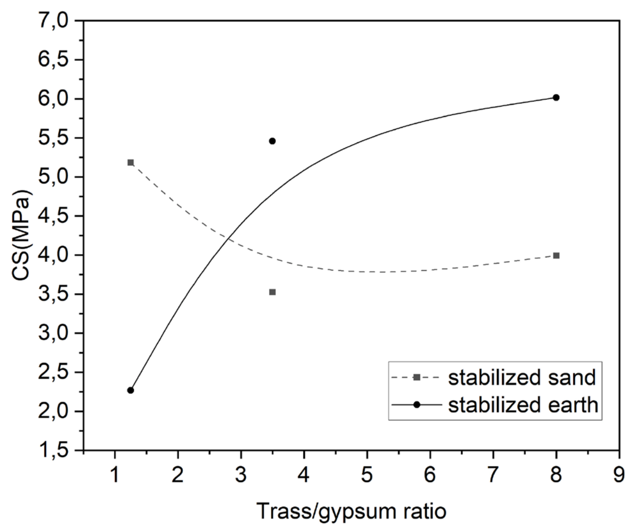

Figure 40: 28day CS versus trass/gypsum ratio. Comparison of SES with SSS

The hight strength value at a very high gypsum content observed by SSS is basically due to hydrated gypsum. As shown in Figure 41, the effect of gypsum hydration continues at a certain level where the trass/gypsum ratio reaches 1,25. Up until a trass/gypsum ratio of 2 strength remains stable and then increases again, which can be explained by the increased pozzolanicity and therefore, the formation of water-insoluble pozzolanic compounds.

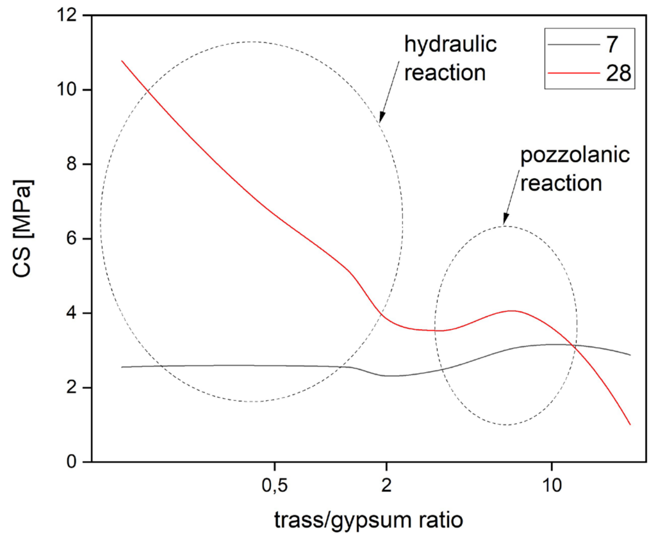

Figure 41: Reaction character at different trass/gypsum ratios

The tests on SES were focused on the areas where the pozzolanic reactions were expected to take place. Therefore, the mix-design combinations were reduced to trass/gypsum/lime percentages of 10/8/2,5, 14/4/2,5 and 16/2/2,5. A summary of the SP test on SES is plotted in Table 16.

Table 16: Maximum strength values of mix-designs after 28 days of curing.

Earth [% of mass]	mix-design combination [% of mass of earth]	Maximum Compressive Strength [MPa]		
Clay/sand	Trass/gypsum/lime	16% water [% of mass of total dry mix]	20% water [% of mass of total dry mix]	25% water [% of mass of total dry mix]
30/70	Plain earth	2,16	1,64	1,05
30/70	10/8/2,5	4,18	2,27	1,13
30/70	14/4/2,5	7,78	5,46	3,87
30/70	16/2/2,5	8,60	6,02	4,65

Maximum CS was achieved by 16% water addition. This value is 43% better than the value achieved by 20% water and 72% better than the value achieved by 25% water. It is important to note that specimens with 16% water needed to be compacted, but specimens can be cast without compaction if 20% water is added.

Moreover, according to the results, the earth-mix with 16wt% trass + 2wt% gypsum (trass/gypsum ratio 8/1) presents the highest strength after 28 days of curing. We can conclude that the SES stabilized with 16% trass, 2% gypsum and 2,5% lime exhibit better mechanical behaviour whether they are dry or wet.

Furthermore, results have proven that the mix-design containing only trass and lime but no gypsum, shows a very low pozzolanicity. Even after 28 days of curing the CS of trass+lime mixture was 1,85 MPa. This clearly means that gypsum as a source of sulphate, plays a key role in the proposed stabilization approach.

4.1.2 Characterisation of stabilization effect through XRD analyses

The preparation process of specimens for XRD measurement can be seen in Appendix D. The labelling of the mix-design powder samples used for X-ray diffraction (XRD) analyses are given in Table 17.

Table 17: Labelling of SES used for XRD analyses

Labelling	T5G13L2.5	T10G8L2.5	T14G4L2.5	T16G2L2.5	T10G8N2.5
Description	5wt% trass, 13wt% gypsum and 2.5wt% lime	10wt% trass, 8wt% gypsum and 2.5wt% lime	14wt% trass, 4wt% gypsum and 2.5wt% lime	16wt% trass, 2wt% gypsum and 2.5wt% lime	10wt% trass, 8wt% gypsum and NaOH equal to 2.5wt % lime

The XRD results of all 7day-cured mix-design powders are plotted together in Figure 42.

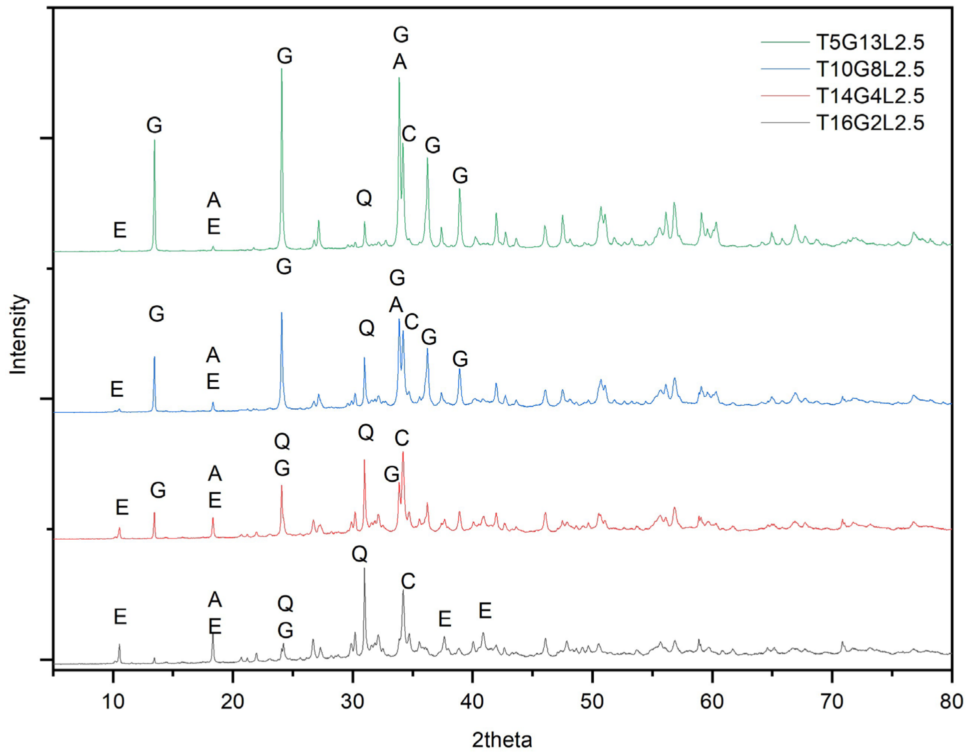

Figure 42: 7 days XRD pattern of the studied mixes of additives (without earth). (E; Ettringite, G; Gypsum, A; Analcime, Q; Quartz, C; Calcite)

As can be seen in the XRD pattern, T5G13L2,5 and T10G8L2,5 display high amounts of gypsum. Very weak peaks of ettringite can be observed in T5G13L2,5 and T10G8L2,5. As expected, when trass content is increased, the intensity of gypsum peaks decreases. With the increase of trass content in sample powders, the intensity of the ettringite peaks increases as well. The reason for this behaviour is attributed to the pozzolanic effect of trass.

Moreover, XRD patterns of all 28day-cured mix-design powder samples are plotted in Figure 43. As with 7day results, the intensity of gypsum peaks of samples T5G13L2,5 and T10G8L2,5 is remarkably high and very weak ettringite peaks were identified in these powders. However, with the increase of the trass/gypsum ratio, the ettringite peaks increase as well.

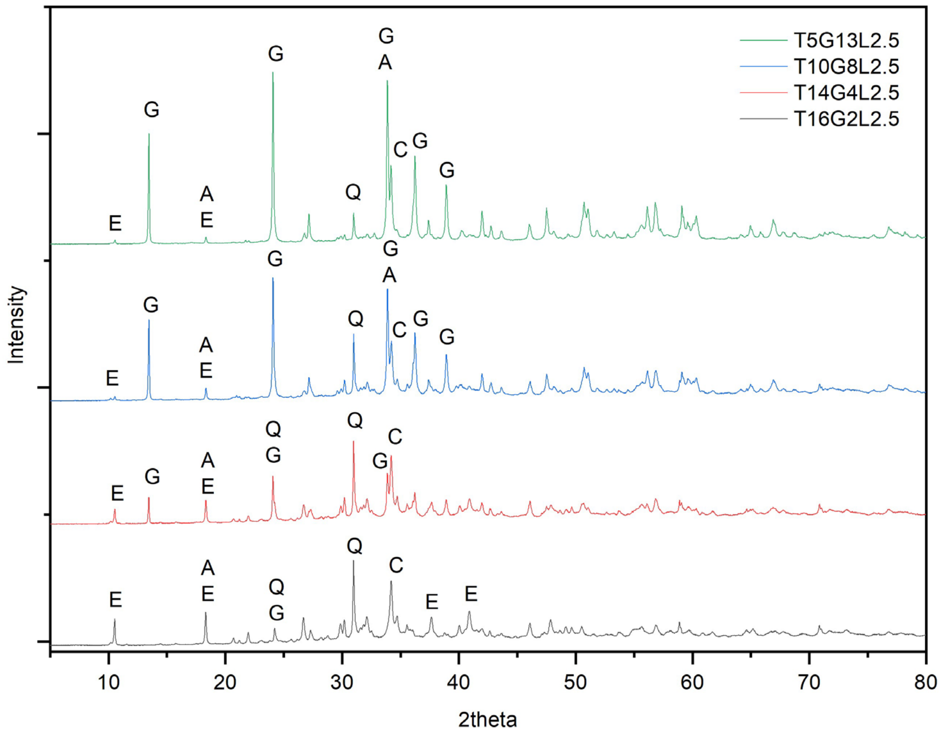

Figure 43: 28day XRD pattern of the studied mixes of additives (without earth). (E; Ettringite, G; Gypsum, A; Analcime, Q; Quartz, C; Calcite)

The detailed quantitative analyses of the XRD powder samples of various mix-designs are given in Table 18 below.

Table 18: Mineralogical composition of the mix-design powders according to XRD analyses

Sample	TGL5132.5		TGL1082.5		TGL1442.5		TGL1622.5	
Mineral	7d	28d	7d	28d	7d	28d	7d	28d
Analcimecubic/sum	1,7	1,6	4,0	4,2	5,8	6,0	7,3	6,6
Biotite1MFeref/sum	0,4	0,3	1,5	1,4	2,3	2,9	3,0	2,9
Calcite/sum	18,7	15,8	17,3	14,3	17,0	14,2	15,9	14,7
PlagioclaseAlbite/sum	1,6	1,7	2,9	2,6	3,6	3,3	4,0	3,8
Quartz/sum	2,4	2,8	5,0	5,4	7,4	7,2	8,7	8,1
Ettringite/sum	2,6	5,7	5,9	6,7	12,8	17,4	20,3	26,9
Muscovite2M1/sum	3,0	2,4	4,1	3,9	4,5	5,7	5,4	6,0
Orthoclase/sum	5,3	5,7	10,5	11,0	14,0	15,6	18,1	17,7
Gypsum/sum	55,0	54,1	37,0	38,0	21,2	14,8	4,5	<0.2
Thenardite/sum								
Dolomite/sum	6,4	6,4	4,1	4,4	1,4	3,0	1,4	2,1
Portlandite	<0.2	<0.2	0,6	0,5	0,8	0,7	1,0	0,7
Smectitedi2Wfix	1,7	3,4	5,6	6,9	7,8	8,4	9,2	10,4
KaolsimpleKGa2	1,2	<0.6	1,5	0,7	1,4	0,7	1,2	<0.6
%	100,0	99,9	100,0	100,0	100,0	99,9	100,0	99,9
%-amorphous	17,9	19,9	26,5	26,8	32,8	36,3	36,5	40,6
(from DiffracEVA)								
analcime/ettringite	0,6	0,3	0,7	0,6	0,5	0,3	0,4	0,2

According to the table, two factors affect the increase of amorphous content: the increase of trass content and the curing time. Except for T10G8L2,5 in all 28day cured powders, around 10% more amorphous content was identified when compared to 7day cured powders.

Moreover, the minerals such as biotite or quartz, which were identified in trass powder or plagioclaseAlbite, muscovite or smectite, which were found in clay powder could also be identified in mix-design powders. However, as mentioned at the beginning of this chapter, there was no clay content in XRD samples.

The chemical additives react with particles of trass to produce hydration products such as ettringite ($Ca_6Al_2(SO_4)_3(OH)_{12}\cdot 26H_2O$). A part of aluminium is being consumed by the formation of ettringite. Moreover, analcime ($NaAlSi_2O_6\cdot H_2O$) was found in all samples, which also contain aluminium. This may be the Aluminium in trass powder, which was not consumed by pozzolanic reactions. On the other hand, a notable amount of calcite was observed in all series.

In addition, the most relevant mineralogical compounds identified in 7 and 28day cured powder samples have been plotted together in Figure 44 and Figure 45. As can be seen in the graphs, all powders contain a significant amount of unreacted calcite. From 7 to 28day only a slight decrease in calcite content was observed. The amount of portlandite found in all sample powders was between 0 to 1%. Both calcite and portlandite are being consumed from 7 to 28 days.

XRD results clearly showed that ettringite precipitation decreases when gypsum content increases.

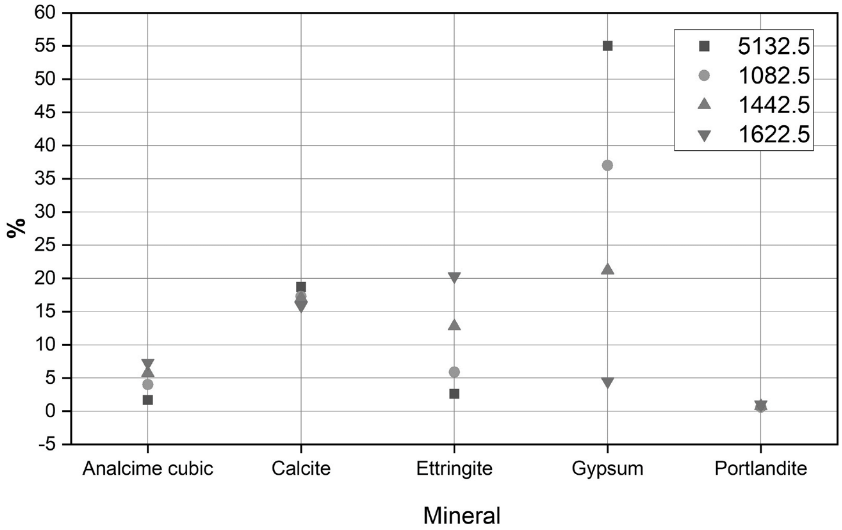

Figure 44: The mineralogical composition of 7day cured mix-design powders according to XRD analyses

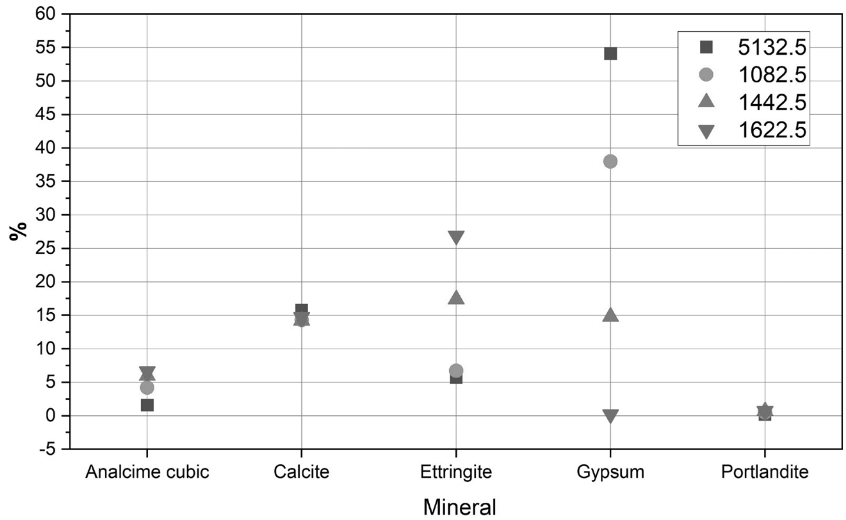

Figure 45: The mineralogical composition of 28day cured mix-design powders according to XRD analyses

Moreover, NaOH was used instead of lime addition to further investigate the pozzolanicity of the mix-design proportions. For this purpose, as with SP tests, the mix design with 10% trass and 8% gypsum was used as a reference. 7day and 28day XRD analyses result of T10G10N2,5 are shown in Figure 46.

In comparison with specimens without NaOH, thenardite was found in T10G10N2,5. Thenardite is any type of sodium sulphate mineral (Na_2SO_4) [126] and, is anhydrous [127]. According to Doehne et al. 2001 in wet conditions, thenardite crystals generally dissolve, rather than hydrate, resulting in extremely rapid crystallization [128] and they stated that this causes little damage.

Furthermore, when compared with 7day curing, after 28 days, where gypsum and thenardite peaks decrease, ettringite peaks increase.

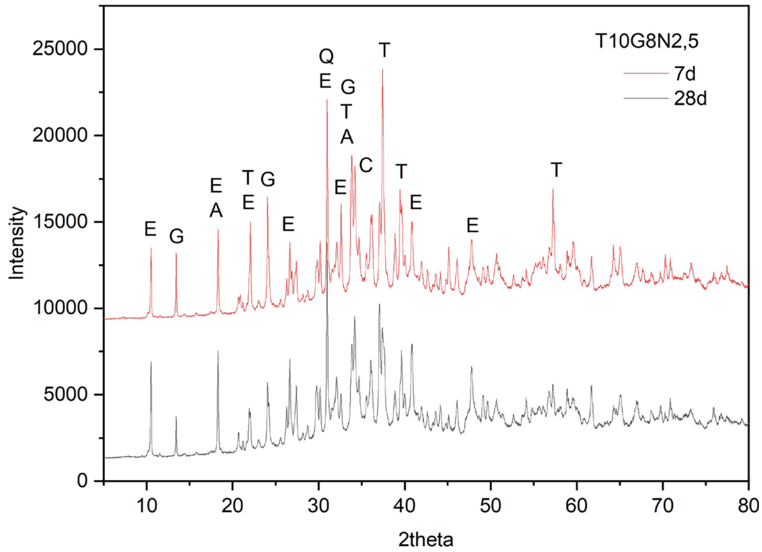

Figure 46: 7 and 28day XRD analyses result of mix-design T10G8N2.5

A comparison of 28day XRD analyses of T10G10N2,5 and T10G10L2,5 is plotted in Figure 47. The graph shows that when NaOH is used instead of lime, the precipitation of ettringite increases remarkably, which can be explained with an increase of pozzolanic activity.

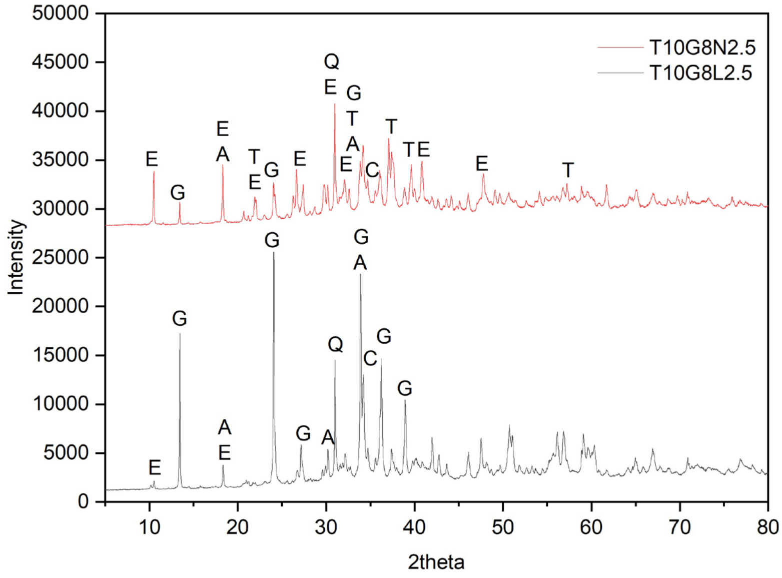

Figure 47: Comparison of 28day XRD analyses result of mix-design T10G10N2.5 and T10G10L2.5

4.1.2.1 Summary of the chapter

Ettringite, which is a common cementitious material and responsible for the material's strength, was identified in all specimens. Precipitation of ettringite increases from 7 to 28 days of curing. NaOH contributes to the improvement of pozzolanicity, however, further experiments needed to better characterize its effect on pozzolanicity of the investigated mixtures. By longer curing time, calcite and portlandite peaks decrease. Moreover, although gypsum in the mixture is the source of sulphate, increasing the gypsum content in mix-design did not contribute to the formation of ettringite as gypsum hydrated immediately.

XRD analyses have proved that not only hydrated gypsum but especially with the increased amount of trass ettringite, the product of pozzolanic reactions steps forward by the strength of the mix-design.

4.1.3 Shrinkage

The equipment used for shrinkage measurement can be seen in Appendix E. The labelling of the specimens is given in Table 19.

Table 19: The labelling and mixture proportions of the specimens used for shrinkage measurements

Label-ling	PE	T5G13	T10G8	T14G4	T16G2
Descrip-tion	Plain earth with 30% terrasol and 70% standard sand	Earth with 5wt% trass, 13wt% of gypsum and 2.5wt% of lime	Earth with 10wt% trass, 8wt% of gypsum and 2.5wt% of lime	Earth with 14wt% trass, 4wt% of gypsum and 2.5wt% of lime	Earth with 16wt% trass, 2wt% of gypsum and 2.5wt% of lime

4.1.3.1 Shrinkage with 16% of water content

The shrinkage measurement of the SES and plain earth cast with 16 wt% of water can be seen in Figure 48. As expected, the plain earth presented the highest shrinkage. Maximum drying shrinkage values of T14G4, T16G2, T10G8, and T5G13 mixtures were, 0,44 – 0,40 – 0,36, and 0,27% respectively. With the increasing amount of gypsum in the mixture, the shrinkage decreases. This is due to the rapid consumption of water through the hydration of gypsum. Moreover, the low shrinkage of T5G13 can be attributed to a rigid skeleton formed by a rapid hardening of gypsum in the structure. As the results show, the shrinkage of specimens within 14 days is remarkably high. Between 14 days and 56 days the change in shrinkage value is low. Therefore, the more gypsum content in the mixture the less shrinkage of the specimen within 14 days. On the other hand, precipitation of water-insoluble compounds of the pozzolanic reactions is a long-term process. Therefore, the stabilization effect of pozzolanic reactions seems to contribute less to the reduction of shrinkage.

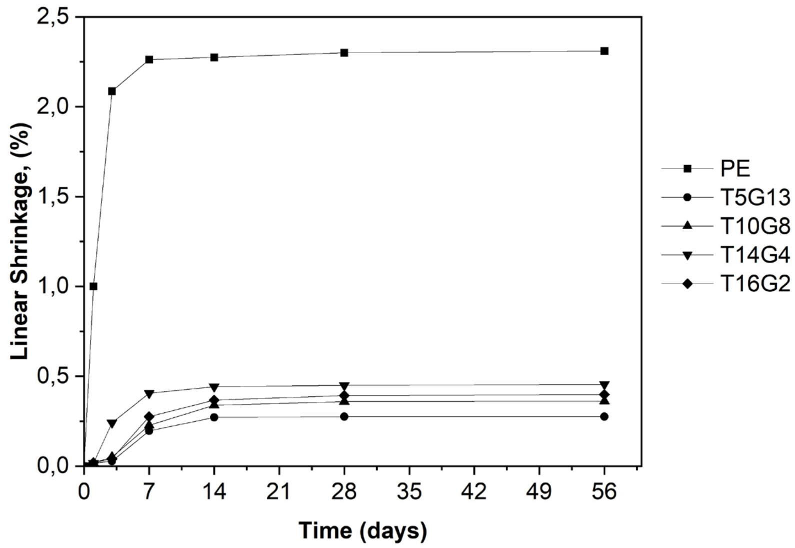

Figure 48: Drying shrinkage of SES and plain earth by 16% water content

4.1.3.2 Shrinkage with 20% of water content

The results of measurement with 20 wt% water content can be seen in Figure 49. As can be seen from the graph, shrinkage of all stabilized specimens increases by about 7 to 10% by increasing the water content from 16% to 20%. The effect of increased water content in the mixture is more dramatic in specimens with the highest gypsum content.

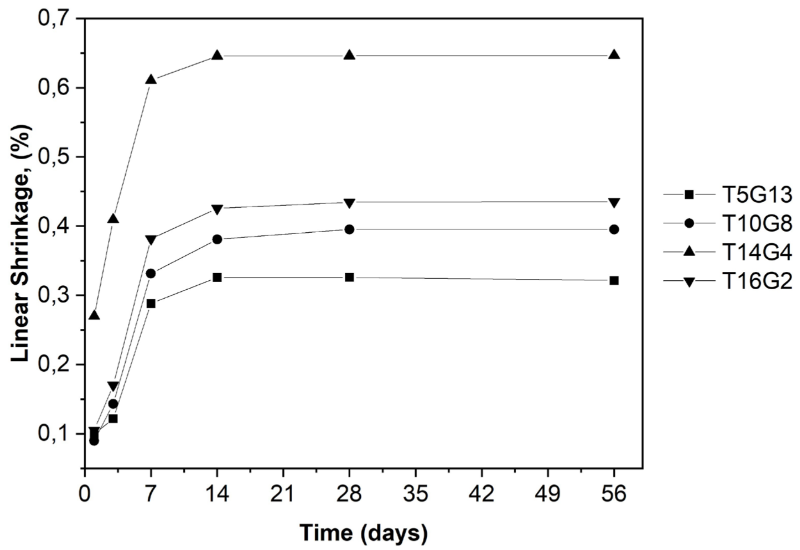

Figure 49: Drying shrinkage of SES by 20% water content

4.1.3.4 Summary of shrinkage measurements

A summary of the shrinkage measurement results on various mix-designs is plotted in Table 20.

Table 20: Maximum Linear shrinkage value of mix-designs after 56 days.

Earth [% of mass]	mix-design combination [% of mass of earth]	Maximum shrinkage value [%]	
Clay/sand	Trass/gypsum/lime	16% water [% of mass of total dry mix]	20% water [% of mass of total dry mix]
30/70	Plain earth	2,31	-
30/70	5/13/2,5	0,27	0,32
30/70	10/8/2,5	0,36	0,39
30/70	14/4/2,5	0,45	0,65
30/70	16/2/2,5	0,39	0,43

It is known that the shrinkage value of normal strength concrete is approximately 0.10-0.15% (Mehta and Monterio 2006) [61]. The average linear shrinkage (LS) value (0,36%) of tested SESs with 16% water, is 3 times, and the average LS value (0,45%) with 20% water is ca. 4 times higher than that of normal strength concrete.

A low shrinkage value is quite a significant property of materials in preventing cracks on buildings. However, based on the observations on SES performed 2 years after, no observable cracks due to shrinkage have been formed on these samples. Although specimens T14G4 have higher gypsum content than T16G2, it could not be explained why they both showed both by 16 and 20% water content higher shrinkage than T16G2.

Moreover, according to the results, shrinkage of the stabilized earth mixtures used in this study is very much related to the gypsum content. Results have shown that the higher the gypsum content, the less the shrinkage. Therefore, mix-design with trass/gypsum ratio of 8 and 20 wt% water shows the highest shrinkage, which is about 0,43%. This value is about 0,39% by 16 wt% water addition. However, 16 wt% water content is suitable for compaction but not sufficient for casting without compaction.

Studies on the shrinkage characteristics of stabilized earth are mainly focused on the shrinkage of cement stabilized rammed earth. A table as an overview showing the acceptable shrinkage values of rammed earth is published by Woyciechowski et al. 2017 [81]. According to this table, acceptable values of linear shrinkage vary between 2,5% (Australia), to 0,5% [129] (New Zealand). According to DIN 18947:2018-1[130], the LS of earthen plasters should be less than

2%. Also, in DIN 18946:2018-12 it is stated that the LS value for earthen mortars should be less than 2,5% [131].

All of the tested earth mixtures with additives and 16% water addition met the shrinkage requirements, even better than that found in New Zealand standard, which requires the lowest value ≤0.5 for cement stabilized rammed earth.

4.1.4 Setting time of stabilized earth mixture

The VICAT setting time measurement apparatus with its parts have been shown in Appendix F. The labelling of the stabilized earth specimen pastes used for Vicat test is given in Table 21 below.

Table 21: The labelling and mixture proportions of the specimens

Label-ling	PE	T0G20.5	T0G18	T5G13	T10G8	T14G4	T16G2	T18G0
Descrip-tion	Plain earth with 30% terrasol, 70% sand	Earth with 20,5wt% gypsum, 2.5wt% lime	Earth with 18wt% gypsum, 2.5wt% lime	Earth with 5wt% trass, 13wt% gypsum, 2.5wt% lime	Earth with 10wt% trass, 8wt% gypsum, 2.5wt% lime	Earth with 14wt% trass, 4wt% gypsum, 2.5wt% lime	Earth with 16wt% trass, 2wt% gypsum, 2.5wt% lime	Earth with 18wt% trass, 2.5wt% lime

Figure 50 shows the setting curve of various specimens during the first 24h. Together with the plain earth 7 stabilized earth pates were measured. With all specimens it was observed that, just after mixing, there is no initial resistance to the shearing of the needle. An abrupt increase in the shear strength is then observed, around 0.1h for T0G20.5 and T0G18 and around 0.13h, 0.17, 1, 0.48 and 3.5h for stabilized earth pastes T5G13, T10G8, T14G4, T16G2 and T18G0, respectively. Penetration resistance increases until the final setting time is reached at 0.15, 0.22, 0.27, 0.28, 8.58, 14.75, and 23.00 h for T0G20,5, T0G18, T5G13, T10G8, T14G4, T16G2 and T18G0, respectively.

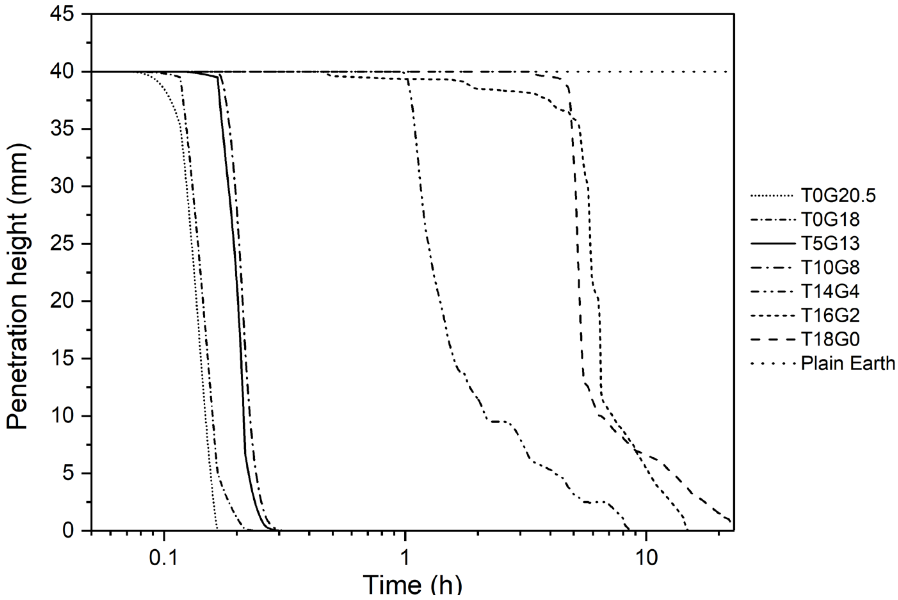

Figure 50: VICAT Setting time of stabilized earth pastes

According to the graph, the setting behaviour of the pastes may be dominated by gypsum content so that one can talk about two groups of pastes. Specimens with high gypsum content are named group I, and specimens with high trass content group II. Figure 51 and Figure 52 show the initial and final settings of these groups.

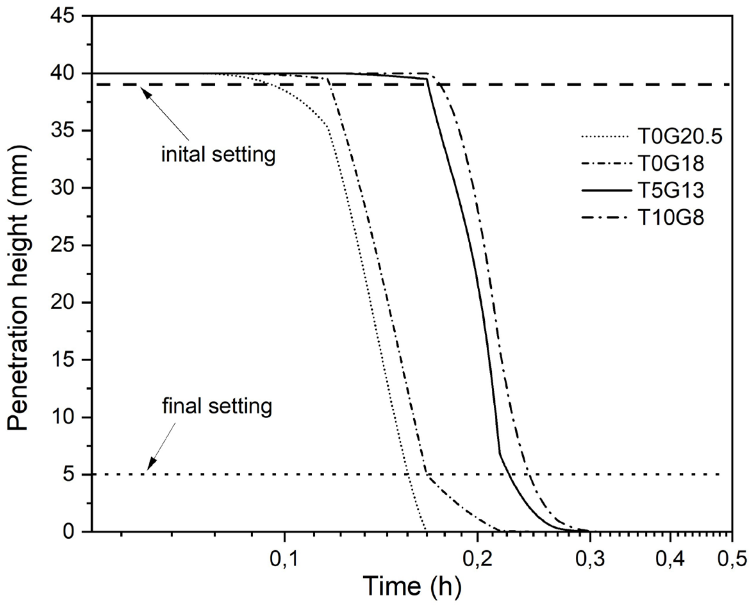

Figure 51: Initial and final setting of stabilized specimens with high gypsum content (group I).

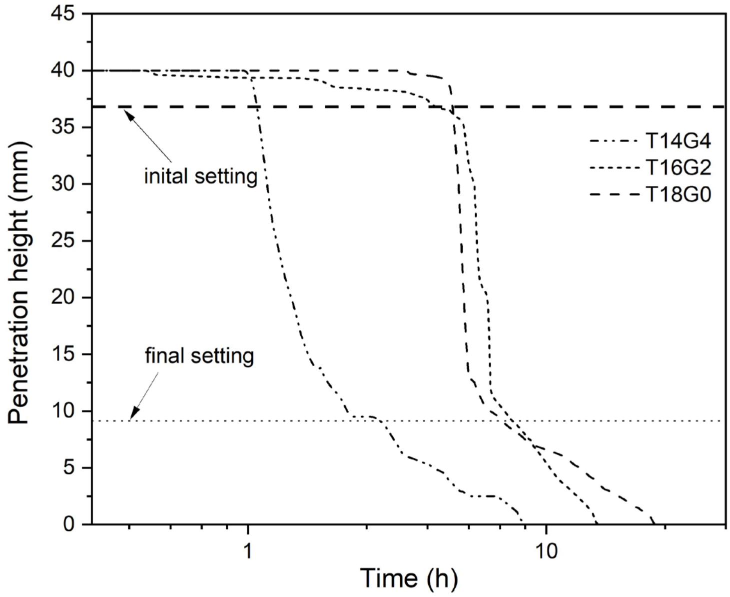

Figure 52: Initial and final setting of specimens with high trass content (group II).

As can be observed from the graphs, the final setting of the specimens with high trass content (group II) is significantly longer than those with high gypsum content (group I). Moreover, as can be seen in Figure 50, all setting curves appear Z-shape, which can be divided into three stages [132]. A detailed analysis of a Vicat setting curve has been done by She Wei et al. 2014.

These stages have been projected for both groups in graphs shown in Figure 53 and Figure 54. Specifically, three stages are defined based on penetration curves.

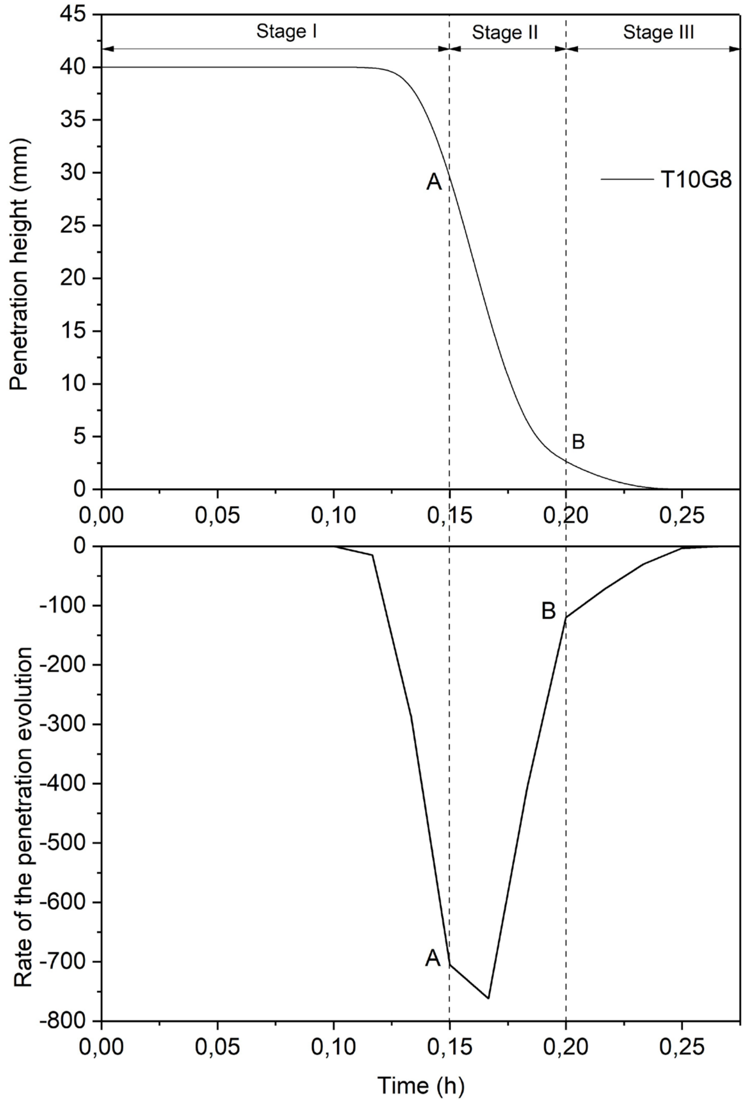

Figure 53: Vicat setting time of earth with 10% trass, 8% gypsum and 2,5% lime

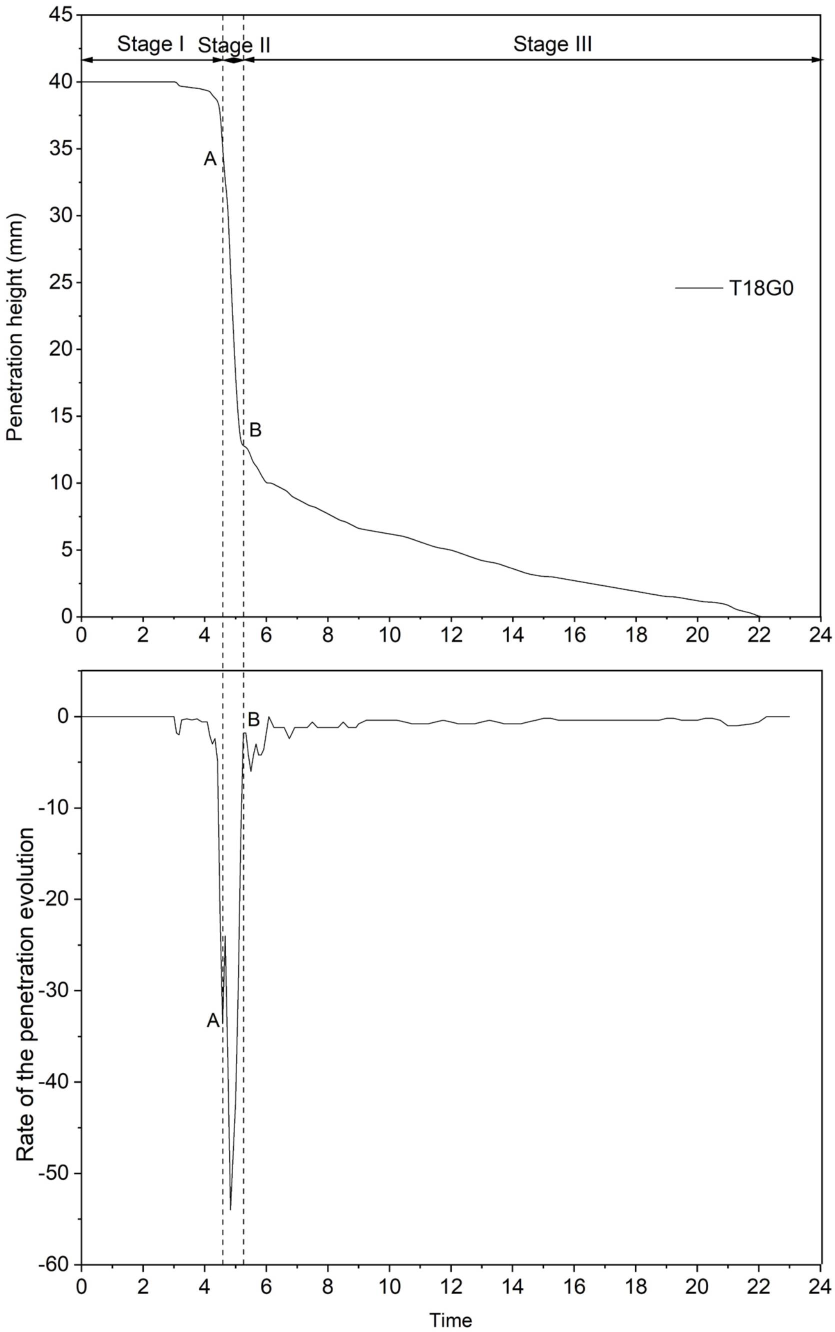

Figure 54: Vicat setting time of earth with 18% trass and 2,5% lime

Stage I (0->A) The penetration remains constant at a relatively low value. It is assumed that during this period, a large number of gypsum particles adsorbed water from the mixture. Depending on the mix-design paste the hydration rate of gypsum is initially very low. The needle penetrates through the viscous earth paste. According to She et al. 2014, this period is generally referred to as the ''dormant stage'' [132].

Stage II (A->B), after the dormant period, the penetration begins to rapidly decrease. This indicates that a great amount of hydration product is formed, resulting in a more solid phase becoming connected. As hydration proceeds, more and more new solid connections are continuously produced until all solid phases are connected throughout the mixture.

Stage III (B->∞), after point B, the needle penetration very slowly decreases and gradually becomes levels off at later ages. This suggests that most of the solid phases have been connected. Ye et al. 2003 and She et al. 2014 mentioned that the slight decrease in penetration curve is due to the fact that micro-pores (less than 1μm) are filled up by a small quantity of hydration products [132], [133].

Although according to Boumiz et al. 1996, Ye et al. 2003, and She at al. 2014 the time between reaching to the point A and point B is very important to characterize the hydration process and microstructure formation process at early ages of cementitious materials. No other analyses were carried out to further investigate hydration formation and microstructure formation of the pastes.

4.1.4.1 Summary of Vicat setting

When gypsum content is higher than 40% of the total amount of additives, setting time is dominated both in initial and final setting phases with the hydration of gypsum. It is assumed that the hydration of gypsum in specimens with high trass content is being retarded through lime and/or trass so that the final setting at which pozzolanic reactions may dominate the setting process can take place. Therefore, the final setting of the specimens with high trass but less gypsum content is around 15h, which can be explained with the pozzolanic reactions but not with natural curing of the paste, as the penetration level of the plain earth was, even after 24 h, still by 40mm and the plain earth paste was observed to still be soft after 48h under laboratory conditions.

4.1.4.2 Effect of retarders on setting time

To investigate the effect of citric acid on the setting of the earth with admixtures, mix-design combination TGL (Trass+Gypsum+Lime) with 16% trass+2% gypsum+2,5% lime was used. The results of VICAT setting time measurement with various citric acid (CA) content are plotted in Figure 55.

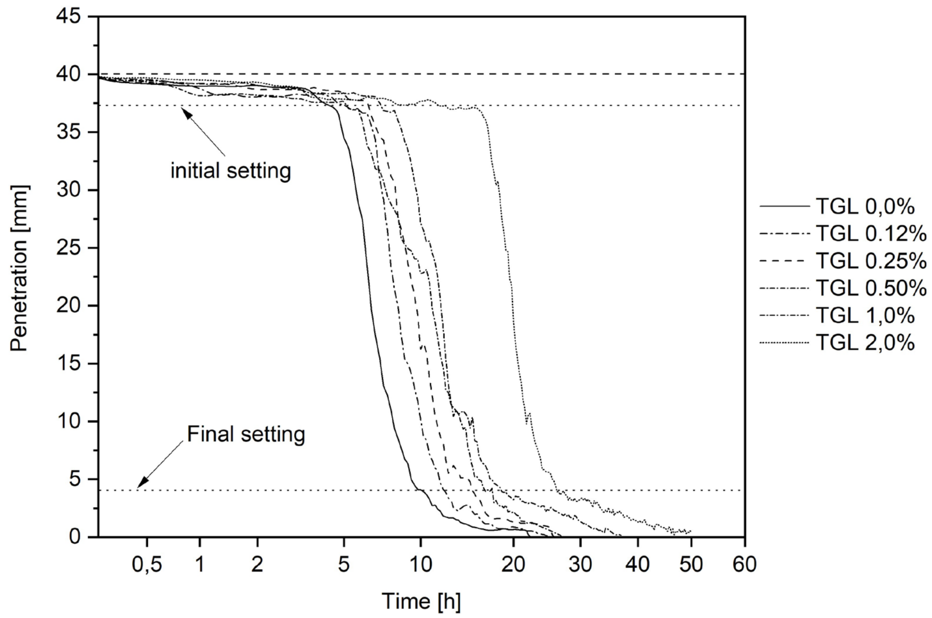

Figure 55: VICAT setting time of TGL with different amounts of citric acid

Results have shown that the initial setting of TGL without CA is about 5 hours. 0,12% and 0,25% CA has retarded the initial setting of the mixture up to ca. two hours, however, had an insignificant retarding effect on the final setting. On the contrary, where 1% of CA retarded the initial setting up to 5 hours, 2% retarded up to ca. 18 hours. 2% of CA has prolonged the initial setting up to ca. 15 hours, and the final setting up to ca. 25 hours compared to TGL without CA.

Moreover, Figure 56 shows the setting time and bounded water versus CA content. With the help of TGA[45], the amount of bounded water has been calculated. TGA has shown that with the increasing amount of CA in the mixture where the setting time increases, as expected the amount bounded water decreases.

[45] Thermographic analysis

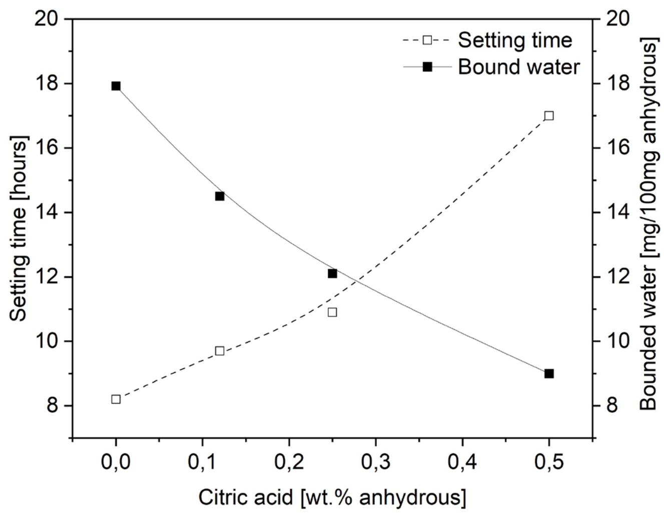

Figure 56: Setting time, bounded water relationship versus different citric acid content

Besides, as mentioned in 4.1.2 the XRD analyses on TGL mixtures has shown that, the highest amount of ettringite was found in TGL mix with 16% trass + 2% gypsum + 2,5% lime. XRD analyses on TGL mixture with CA has shown that, precipitation of ettringite crystalline dramatically decreases when CA content in the mixture increases (see Figure 57 below).

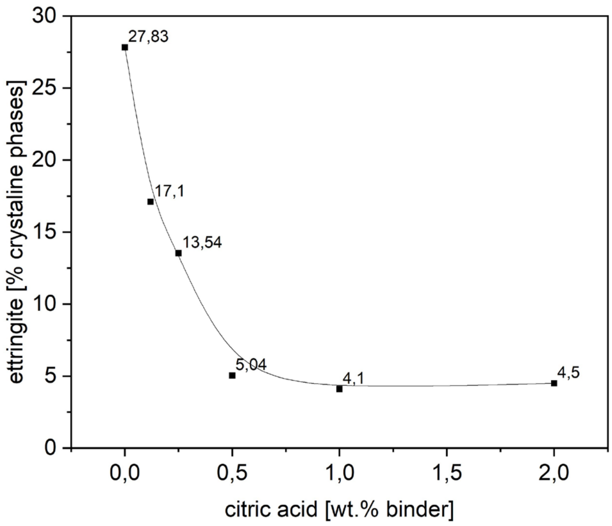

Figure 57: Precipitation of ettringite versus citric acid in the mix-design

4.1.4.2.1 Summary

Results have shown that citric acid can be efficiently used to retard the setting of the earth mixture with additives TGL. However, less than 1% CA has not prominent effect on retarding the setting time and better results are obtained up 1-2%.

4.1.5 Bulk density

The calculated dry bulk densities of plain earth and SES (T10G8, T14G4, T16G2) are given in Table 22 below.

As can be seen in Table 22, the plain earth shows the highest dry bulk density of the stabilized specimens. The specimen with the 8 wt% of gypsum presents the lowest dry density. Specimens T14G4 and T16G2 have respectively, an average bulk density of 1,86 and 1,82 g/cm^3.

Table 22: Results of bulk density calculation with Geopyc

specimen	Value1 (g/cm^3)	Value2 (g/cm^3)	Average (g/cm^3)
Plain earth	2,15	2,07	2,11
T10G8	1,77	1,61	1,69
T14G4	1,87	1,85	1,86
T16G2	1,83	1,81	1,82

According to the results, bulk density decreases when stabilizing agents are added to the plain earth. On the other hand, Figure 58 shows the specimens with higher CS show higher density. This may be explained with the rapid filling of the pores through precipitation of pozzolanic reaction products such as ettringite.

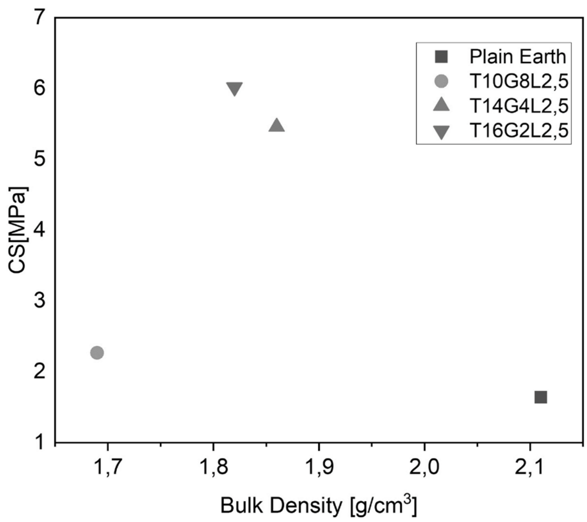

Figure 58: Compressive strength versus bulk density of SES

When gypsum is added to the earth, hydrated gypsum crystals form a microstructural net, which is responsible for the early strength of the stabilized samples while unconsumed water may still exist till the end of curing or drying time. When pore water disappears, it leaves behind a more porous structure than before, which results in the reduction of bulk density.

4.1.6 Porosity

The densities calculated with AccuPyc 1330 He-Pycnometer are given in Table 23.

Table 23: Results of density measurement with Acupyc

specimen	Value1 (g/cm3)	Value2 (g/cm3)	Average (g/cm3)
Plain earth	2,68	2,68	2,68
1082,5	2,66	2,66	2,66
1442,5	2,65	2,66	2,66
1622,5	2,66	2,65	2,65

The ratio of the volume of voids to total volume is defined as porosity [134]. The porosity can be calculated from measurements of particle density ρ_p and bulk density ρ_b [135].

$$\phi = 1 - \rho_b / \rho_p \tag{1}$$

where ϕ is the porosity, ρ_b is the solid mass per total volume of soil, ρ_p is the solid mass per solid volume.

According to this equation, the total porosities of the specimens were calculated as given in the table below.

Table 24: Calculated total porosity of stabilized earth specimens

specimen	Porosity (g/cm^3)
Plain earth	0,21
1082,5	0,36
1442,5	0,30
1622,5	0,31

4.2 Performance tests (durability of mix-design)

Durability, which is defined as the ability of a material to retain stability and integrity over years of exposure to the destructive forces of weathering (Dempsey and Thompson 1968), is an important property of construction materials [136]. The durability studies in the field of soil/earth science are mainly related to stabilized pavements and roads. However, this knowledge is also very applicable in the field of earthen architecture and construction materials made of unfired earth.

4.2.1 Water resistance

One of the main decaying factors in earth constructions is the presence of water. Once plain earth gets in contact with water, it swells, and the dissolution and erosion are inevitable. To overcome this weakness, the stabilization of earth can be a significant application.

4.2.1.1 Water insertion test

The experimental set up of water insertion test can be seen in Appendix I. The loss of mass of the stabilized earth specimens (SES) and plain earth after the water insertion test is plotted in Figure 59.

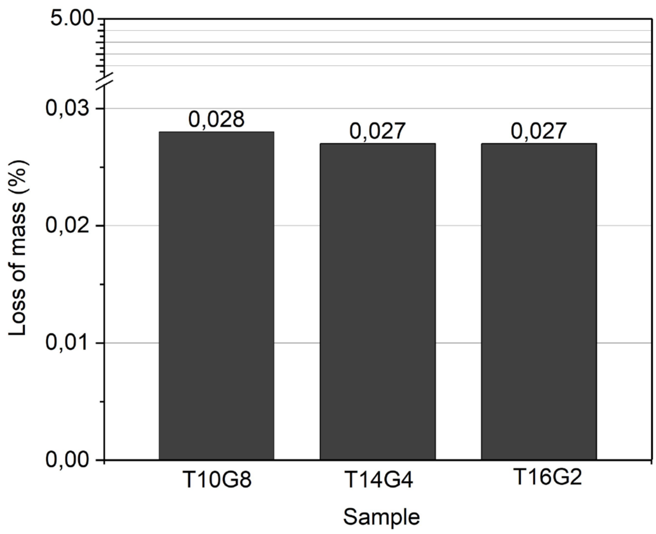

Figure 59: Loss of mass of SES after water insertion test.

According to the water insertion test described in DIN 18945, the loss of mass has to be less than 5% of the total mass in order to be considered as acceptable. After 10 min. of water insertion, the loss of mass of the plain earth samples was determined as 38.41% of the total mass. However, as can be seen in Figure 59 all SES have shown similar behaviour and the loss of mass of the specimens is between 0.02-0.03 percent of total mass, which is significantly, lower than the limit value.

The condition of the plain earth and SES after the insertion test can be seen in Figure 60. No cracks were observed due to swelling: the proposed combination of additives significantly improved the water stability of the earth specimens. However, as observed, the change in trass/gypsum ratio does not influence the water-resistance of the SES.

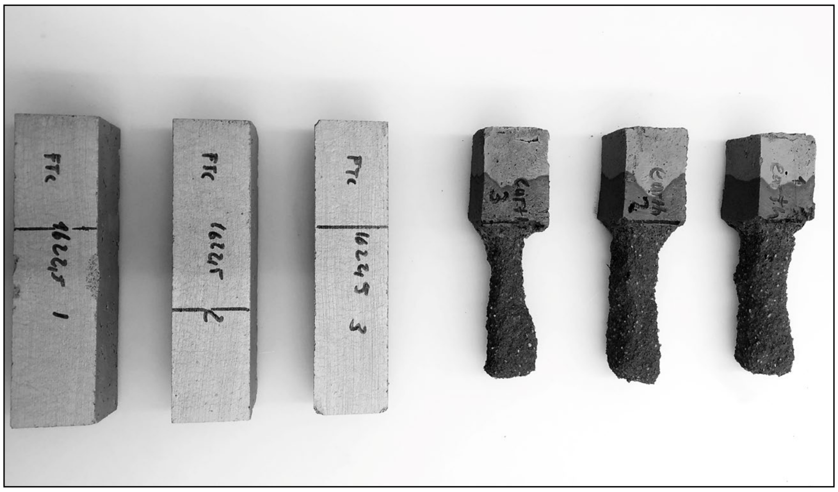

Figure 60: SES and PE after ten minutes of water insertion

4.2.1.2 Capillary water absorption

The experimental set up of capillary water absorption (CWA) can be seen in Appendix J. The relation between absorbed water in the unit area and the square root of time is shown in Figure 61.

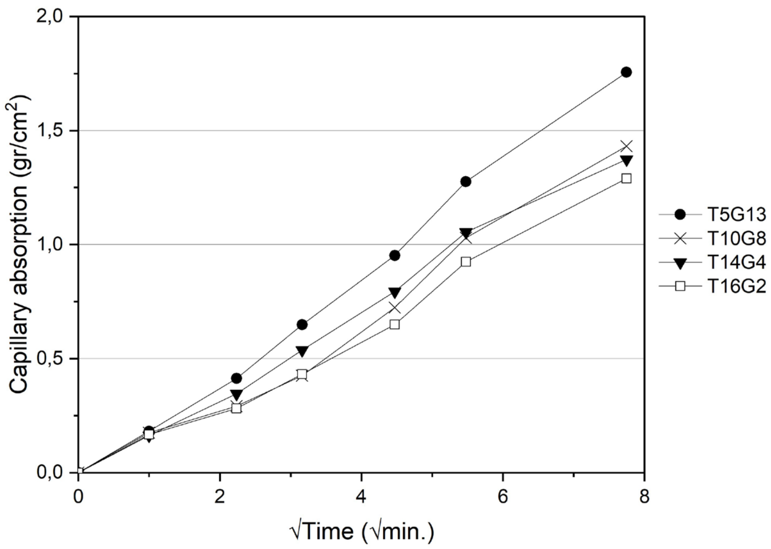

Figure 61: Capillary water absorption curve of SES

At the first hour of the test, CWA of the specimens showed similar behaviour. However, after two hours this behaviour changes. As can be observed from the graph, the CWA of T5G18 is higher than T10G8 and T6G2. According to results, CWA increases when gypsum content in the mixture increases.

Moreover, the capillary water-rise results obtained are plotted in Figure 62 below.

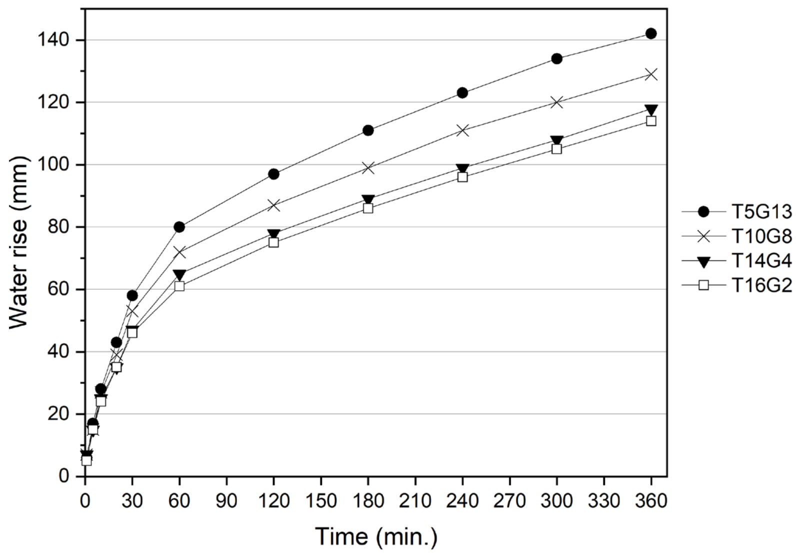

Figure 62: Capillary water rise of the SES

While the water rise rate is highest in the samples containing 5% trass and 13% gypsum (T5G13), it is lowest in samples containing 16% trass and 2% gypsum (T16G2). As observed, all the SES had no erosion following their contact with water. The thin and continuous capillary network causes higher capillary suction. The structure formed by pozzolanic activity keeps specimens undamaged despite their contact with water.

4.2.1.3 Summary of water resistant

The results have shown that the mix-design T16G2 with 16% trass, 2% gypsum and 2,5% lime has the lowest capillary absorption and lowest water rise. This can be attributed to the denser structure of T16G2 compared to T14G4, T10G8 and T5G13.

As discussed in chapter 4.1.2, XRD results showed that specimens with 16% trass, 2% gypsum and 2,5% lime contain more ettringite then the others. CWA has proofed that the mix-design T16G2 has a denser structure as the ettringite fills the capillary networks and therefore, causing a lover capillary suction.

4.2.2 Freeze-thaw effect on durability

The labelling of the samples made of different mix-design proportions and used for the freeze-thaw cycle (FTC) is given in Table 25.

Table 25: Labelling of the specimens used for FTC test.

Labelling	T10G8	T14G4	T16G2
Description	10wt% trass, 8wt% of gypsum and 2.5wt% of lime	14wt% trass, 4wt% of gypsum and 2.5wt% of lime	16wt% trass, 2wt% of gypsum and 2.5wt% of lime

The climate chamber and stabilized earth specimens (SES) used for FTC test can be seen in Appendix K. The FTC temperature process according to DIN is given in Figure 63.

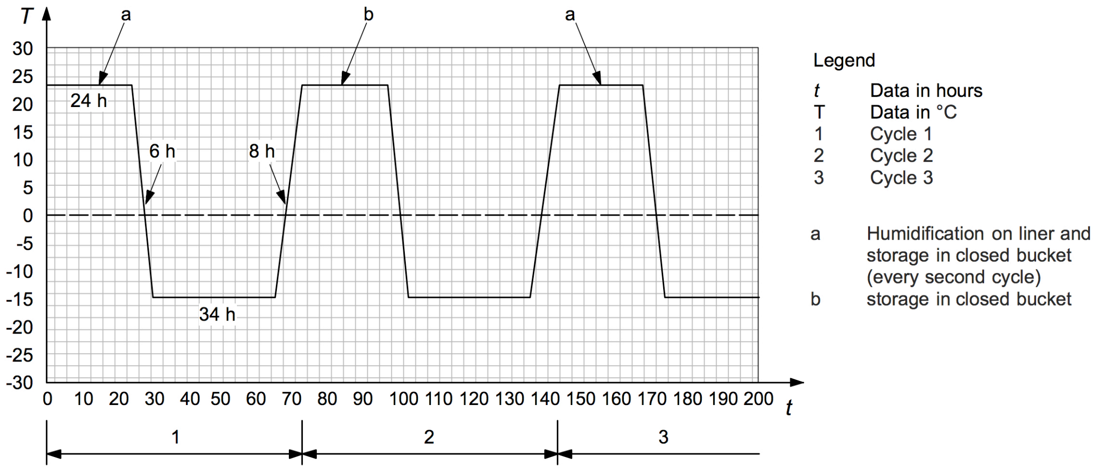

Figure 63: Temperature process of FTC test according to DIN 18945:2013-08

The temperature and humidity versus time graph is given in Figure 64.

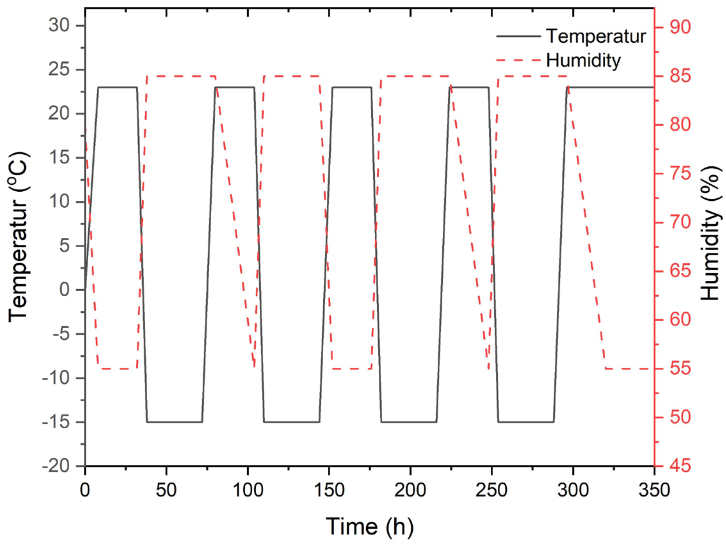

Figure 64: Temperature and humidity of SES with FTC

The length development of the SES after 8 FTC are presented in Figure 65. The water content increased during FTC due to the water absorption during thawing. As a result, the length of the soil specimens also increased with an increasing number of FTC, as shown in Figure 65. Where T10G8 showed lowest length change, T14G4 showed the highest change. However, as can be seen in the figure, after the 5th cycle the volume of SES decreased dramatically.

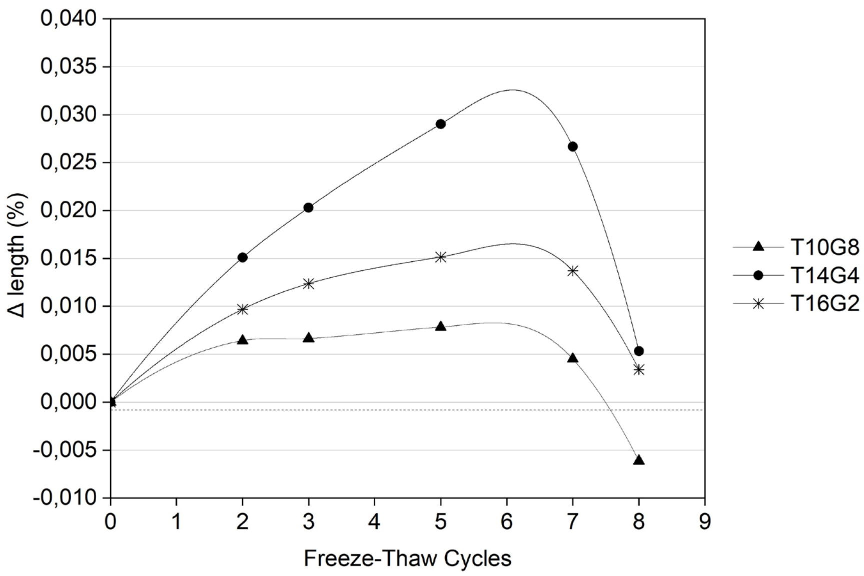

Figure 65: Length development of SES related to FTC test.

Moreover, the weight change of the specimens was also documented. For this purpose, the specimens were stored in the laboratory for one week at 23°C and 50% relative humidity and conditioned to constant mass. The weight of SES was subsequently determined and compared with the values before the FTC test. The results are plotted in Figure 66. While T16G2 and

T14G4 showed loss of weight of circa 1,4%, the T10G8 showed a gain of weight, which might be explained with the further hydration reactions due to the unreacted gypsum and/or lime particles. This may also be due to delayed ettringite formation.

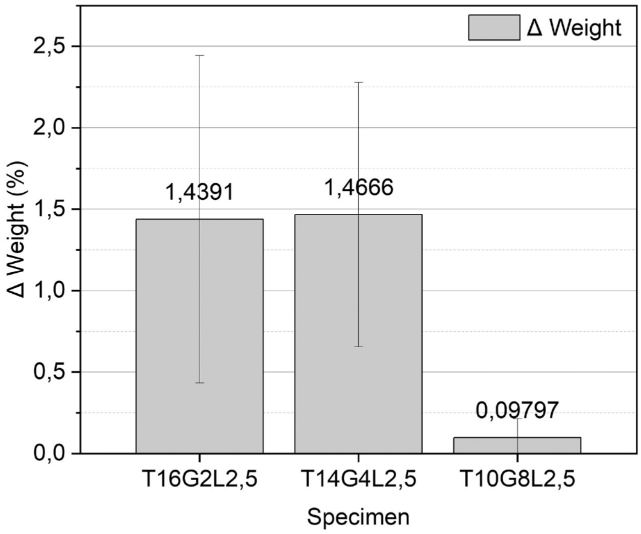

Figure 66: The weight change of the SES after treating FTC.

In this study, the pore characteristics of the SES were not studied. An examination of some of the pore characteristics of the three soils, before and after freeze-thaw treatment, may be helpful [137].

4.2.2.1 Summary

When compared with the initial length, T16G2 and T14G4 have shown an expansion of ca. 0,005%. On the contrary, T10G8 showed a shrinkage of 0,005% in comparison to initial length. Moreover, to exactly investigate the reasons behind the weight change of the SES, further studies are needed as these changes may be due to the damages occurred during the measurements. Also, it is not clear why the specimens showed an expansion until the 5th cycle and then shrink till the end of 8th cycle.

4.2.4 Delayed ettringite formation

The labelling of the samples made of different mix-designs and used for the test is given in Table 26. The casted specimens and water tank with SLW can be seen in Appendix L.

Table 26: Labelling of SES used for saturation test.

Labelling	T8G6L5	T10G8L2,5	T16G2L2,5
Description	8wt% trass, 6wt% of gypsum, and 5wt% of lime	14wt% trass, 4wt% of gypsum, and 2.5wt% of lime	16wt% trass, 2wt% of gypsum, and 2.5wt% of lime

The 56day expansion results of the SES are plotted in Figure 67. According to the measurement after 6 hours of water suction, all of the specimens had expanded. This measurement is called Zero-day measurement as shown in the graph below. T8G6L5 has shown the highest and continuous expansion. On the other hand, T10G8L2,5 and T16G2L2,5 have shown no expansion from zero-day to 14day measurement. On the contrary, they had slightly shrunk.

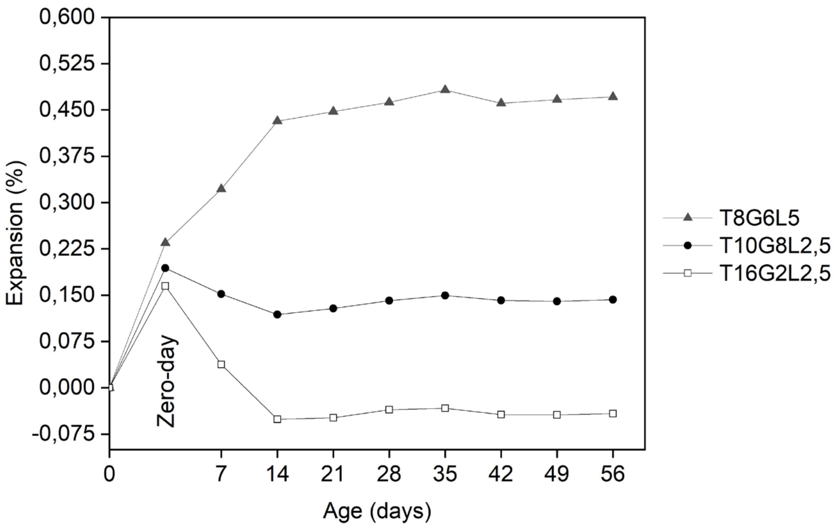

Figure 67: Expansion of SES related to delayed ettringite formation test.

As can be seen from Figure 68, three stages were identified during the whole measurement process. At the first stage (from 0 to 14 days) a significant expansion and expansion-shrinkage were observed. At the second stage (from 14 to 28 days) expansions slowed down significantly and in the last stage (from 28 to 56 days) very minimum changes were observed.

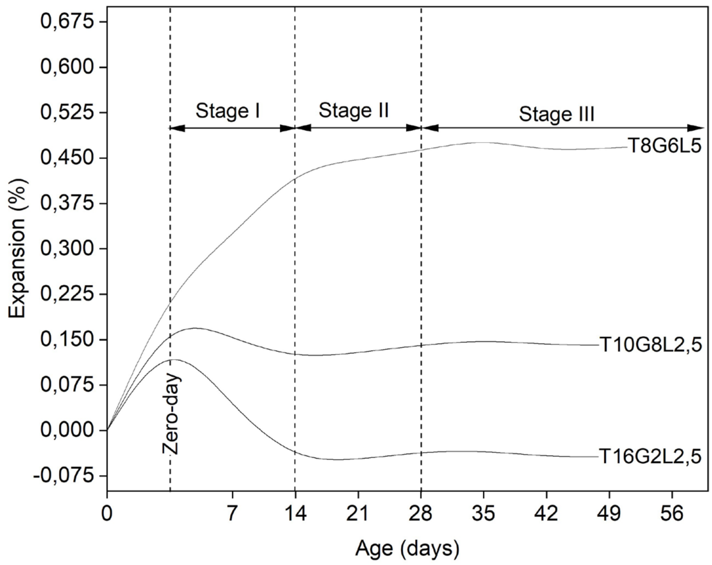

Figure 68: Different stages observed by the expansion of SES.

4.2.4.1 Summary of the DEF

The specimen T8G6L5 was planned to be the most unstable mix-design. Therefore, the lime content was increased up to 5%. As expected, this mixture has shown the most expansive behaviour. This may be attributed to DEF. On the other hand, the mix-designs T10G8L2,5 and T16G2L2,5 showed a parallel, but a very different behaviour then T8G6L5.

4.2.5 Thermal conductivity

To determine the thermal conductivity the mix design T10G8L2,5 was used as a reference mix. The preparation of the specimen and the test apparatus can be seen in Appendix M. The results of the thermal conductivity measurement are given in Table 27 below.

Table 27: Thermal conductivity results measured with KD2 apparatus.

Measurement	Number of measurements	Error	Measured temperature (°C)	Result ($WM^{-1}.K^{-1}$)
1	10	0,0071	23,20	1,191
2	10	0,0050	23,29	1,147

According to the results obtained from the test, the measured average thermal conductivity is 1,16 $WM^{-1}.K^{-1}$.

5 Implementation strategies of the research findings

5.1 Comparison of achieved results compared to general earth stabilization context

5.1.1 Development of ETGL (earth with trass, gypsum and lime)

ETGL developed in this study is a product consist of industrial earth and stabilizing agents (trass, gypsum and lime). The industrial earth, which contains 30% clay and 70% sand, made it possible to eliminate soil excavation and classification as well as soil suitability tests. The stabilizing agents are classified as traditional additives available on the market. The optimum dry ETGL mixture investigated in this study consists of 16wt% trass + 2%wt gypsum + 2,5wt% lime of the dry earth. It is important to ensure a homogenous dry mix. After adding the stabilizing agents to the earth, the total dry-mixture should be mixed about 5 minutes. After the mixing process ETGL is ready for use as stabilized dry earth-mix product. The water addition depends on needs. After water addition the mixture should be homogenously mixed. The mixing process of wet mixture should not be less then 3 minutes. A moist dry mixture can be produced with 16% water addition to the total dry-mix. Where 20% water addition is enough for an extrudable mixture, 25% water addition would be enough for a pourable mixture.

5.1.2 Strength performance (SP)

The results of compressive strength (CS) showed that the CS of plain earth can be significantly improved with the proposed mix design. SP has been discussed under the following points:

- When the clay is not present in the mix-design, gypsum content dominates the strength gain of the specimens. This is due to the hydraulic reaction. But when the clay is present, the effect of pozzolanic reactions on the development of SP becomes dominant. Because as the wet CS tests have shown, when strength gain is achieved by pozzolanic reactions, SES show better performance. Also, best strength results have been obtained by specimens with the highest trass/gypsum ratio, which means less environmental impact and better strength.
- In samples with high gypsum content hydrated gypsum is responsible for the strength, however, wet CS tests have proven that strength gain through gypsum hydration is less efficient. This may be attributed to the soluble character of gypsum crystals. Therefore, earth stabilization with GL (gypsum+lime) addition, which is comprehensively studied by researchers Kafescioğlu et al. and Işık et al, has been further improved through the use of trass with gypsum and lime together.

- More failures or uncertainties have affected the 7day result, such as possible cracks or damages after demoulding were documented. Also, pozzolanic reactions are long term reactions. Therefore, these reactions seem to be less determined by the 7day results. However, after 28 days, strength development seems to be determined by the pozzolanicity of the mixtures. Apparently with the increase of trass/gypsum ratio pozzolanicity has increased, hence, strength increased parallel to this. This has also proven that strength improvement through pozzolanic activity is more efficient than the improvement by means of hydration of gypsum.
- Moreover, results have shown that saturated lime water (SLW) even after 28 days, did not contribute to the pozzolanicity of the mix-design. When SLW used the specimens with high gypsum content showed better strength as gypsum could better hydrate. This result confirmed the research of Kafescioğlu et al., Işık et al., and Pekmezci et al. showing that the lime retards the setting time of gypsum.
- The results with and without clay content in tested specimens have shown that stabilization makes it possible to use soil types regardless of a minimum and maximum amount of clay content in the selected soil. Therefore, stabilization not only improves strength, durability and resistance to water erosion, it may also turn some soils that are initially unsuitable into soils appropriate for construction [14].

Achieved improvement

Cement stabilization praxis has shown that the cement addition for earth stabilization should be between 5-10%. Hence, a summary of some relevant studies and the results is plotted in Table 28.

Table 28: A summary of some relevant studies and the results obtained.

Reference	Earth	additive	CS (MPa)	
Researcher		**%**	**wet**	**dry**
Waziri et al 2013	Clayey gravel/sand	7,5 % cement	-	2,8
Bharat et al 2014	21% clay	8% cement 3% lime	4.4	6,0
Namango 2006	20% clay	9% cement	-	5,9
Nagaraj 2014	30% clay	8% cement	2,2 ca.	
Garg et al. 2014	32% clay	9% cement	3,0 ca	4,5
Ciurileanu et al. 2012	30% earth	8% cement	-	1,8
Houben&Guillaud 1994	Soil Class A and B	2-8% cement	-	2-8
Van Damme et al. 2018	-	10% cement	-	4-8
Minke 2013	-	8% cement	2,2ca	4,2 ca
Cicek et al. 2020	**30% clay**	**4,5% cement**	**-**	**2,5**

There are fewer experiments on the wet CS performance of stabilized earth. According to these results, the average value of CS, which can be obtained by cement stabilization is about 4 MPa. The results of this study have shown that a CS value of 8 MPa can be achieved with TGL stabilization. Additionally, the relevant studies on GL (gypsum+lime) stabilization are given in Table 29.

Table 29: The relevant studies on GL stabilization and the obtained results.

Reference	Earth	additive	CS (MPa)	
Researcher			wet	dry
Vroomen 2007	-	13% gypsum 28,5-21% water	2,0	2,8
Işık et al. 2011	-	10%gypsum+2,5% lime + 15-20% water	-	2-4
Pekmezci et al. 2012	-	10%gypsum+2,5% lime + 15-20% water	-	1,7 ca.

The strength development achieved with TGL combination is significantly ahead of the result obtained by only GL stabilization. It is important to note that this achievement is reached not by increasing the gypsum or lime content used in further studies but even with less gypsum content (2%). A comparison of CS of ETGL with other types of building materials is given in Figure 69. The Figure was adapted from the study of Van Damme et al. 2017.

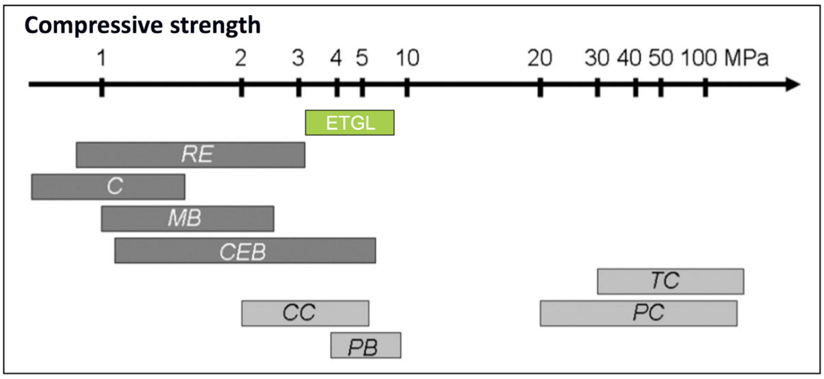

Figure 69: Semi-quantitative compilation of compressive strength of ETGL (earth+trass+gypsum+lime), raw earth, and other reference building materials. Symbols: RE= rammed earth; C = cob; MB = mud brick (or adobe); CEB = compressed earth block; TC =terracotta; PC = plain concrete; CC = cellular concrete; PB = plasterboard. Adapted from [Moevus et al.2013, Moevus et al. 2016, Van Damme et al. 2017]

Another comparison with the CS of various rammed earth specimens as a function, has been plotted in Figure 70.

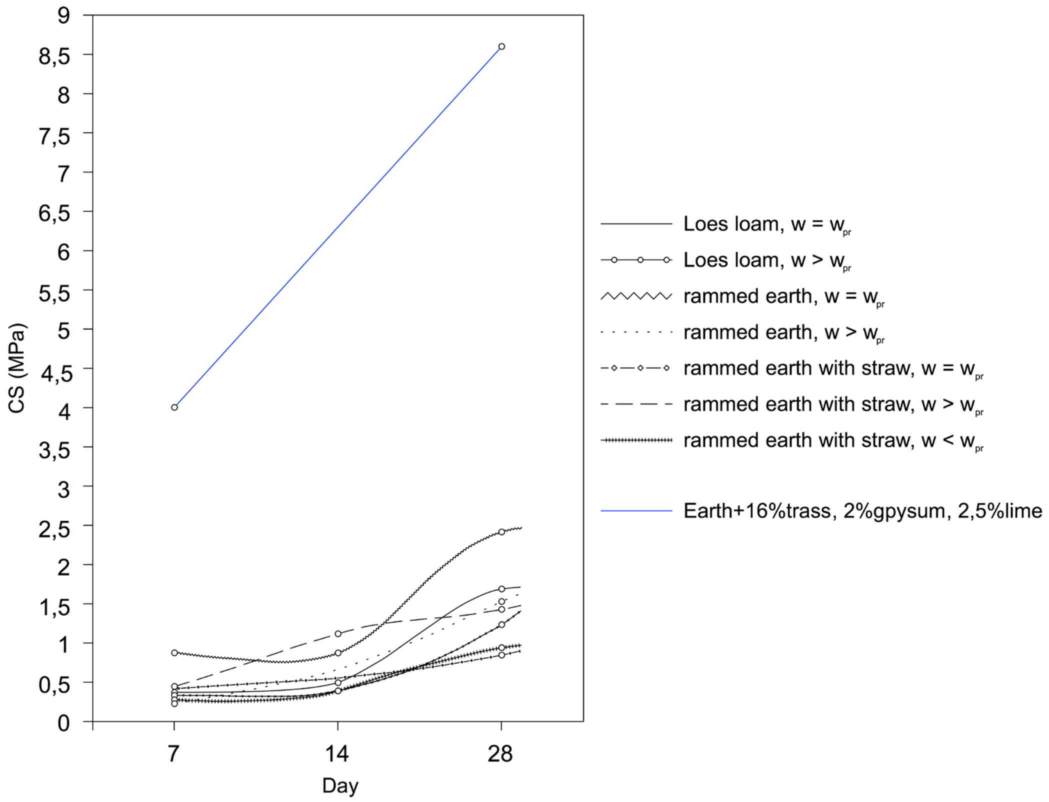

Figure 70: Compilation of results obtained from this study and the CS performance of rammed earth specimens as a function (adopted from Schnellert 2004, Schröder 2010).

As mentioned in chapter 2.4.2, compaction is a mechanical stabilization applied in earthen construction engineering. It is one of the most widely applied construction types in earthen architecture. Ramming is time and energy consuming application. On the contrary, as can be seen in Figure 70, SP of cast (non-compacted) ETGL is significantly ahead of rammed earth types.

5.1.3 Shrinkage

Results have shown that shrinkage values of tested SES are 0,36% (16% water content) on average and 0,44 (20% water content). As in the related studies of Wild et al. 1995, Lopez et al. 2011, and Gadouri et al. 2019, no shrinkage experiments were done. Hence, there is no comparison data available. Also, as stated in the chapter 4.1.3.4, the shrinkage value of trass-gypsum-lime stabilized industrial earth is still 3-4 times higher than that of normal strength cement, which can be still a strong argument for the choice of material.

5.1.4 Bulk density

Stabilizing the earth with trass+gypsum+lime (ETGL) addition has reduced the density of the material. Plain earth used in this study has presented a density of ca 2,11 kg/m^3. Mix-design with 16% trass + 2% gypsum and 2,5% lime (T16G2L2.5) has presented the highest strength performance and the average density of T16G2L2,5 is by 1,82 kg/m^3. Van Damme et al. 2017 [14] has compared various earth-based materials and plain concrete in terms of density. They adapted the table of Moevus et al. 2013, Moevus et al. 2016, Van Damme et al. 2017. The result obtained from this research study has been adapted to this table as shown in Figure 72 below.

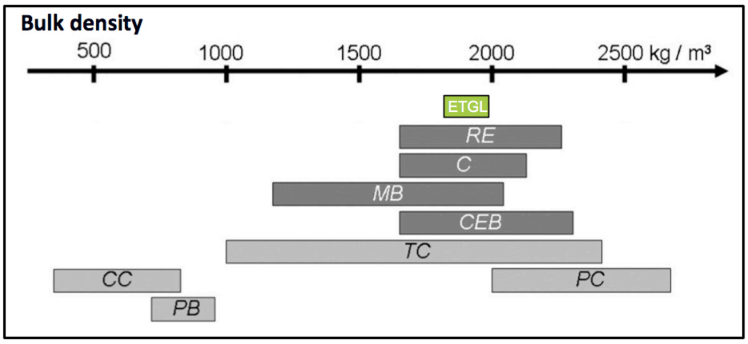

Figure 71: Semi-quantitative compilation of bulk density of ETGL (earth+trass+gypsum+lime), raw earth, and other reference building materials. Symbols: RE= rammed earth; C = cob; MB = mud brick (or adobe); CEB = compressed earth block; TC =terracotta; PC = plain concrete; CC = cellular concrete; PB = plasterboard. Adapted from Moevus et al.2013, Moevus et al. 2016, Van Damme et al. 2017

The ETGL becomes less dense when gypsum content in the mixture is increased. For instance, mix-design T10G8L2,5 has a density of 1,69182 kg/m^3. Finally, ETGL is on average less dense than rammed earth or compressed earth block but shows higher SP than RE and CEB.

5.1.5 Water resistant

For the water insertion test, DIN requires a loss of mass of less than 5%. In this study, the average value of the loss of mass obtained by a water insertion test is 20 times better than that required from DIN. Moreover, results have shown that the capillary suction of ETGL is related to gypsum content in the mixture, so that the higher the gypsum content, the faster the capillary rise. In addition, except for the study of Pekmezci et al. 2012 who used gypsum and lime to stabilize the earth no comparable data was found in the literature related to capillary water behaviour of pozzolan+gypsum+lime stabilized earth.

5.1.6 Freeze-thaw resistance

DIN 1845 states that after the FTC, an assessment must be made of whether the exposed surface has cracks that can be seen with the naked eye or permanent swelling deformations or whether there is any loss of material due to cracks. ETGL specimens showed high resistance to freeze-thaw cycles. No structural cracks were observed by test specimens and the final length change of the test specimens at the end of the test was very minimal (0,05%), which may also be attributed to the humidity change. In addition, although, a 1,4% weight change was documented by specimens with a trass/gypsum ratio of 8 and 3,5, no further experiments were undertaken to explain this phenomenon. A possible reason may be the bonded water through ongoing pozzolanic reactions, due to the humid environment needed for every second FTC.

Esmer et al. 1969 [137] used the unconfined CS test to determine the strength of the specimens exposed to the FTCs. It this study, however, only volume change and weight change of specimens was documented. It may be useful to apply the approach of Esmer et al. in a further study.

Finally, FTC test has demonstrated that the earth stabilized with proposed additives has the potential to withstand even extreme weather conditions.

5.1.7 Thermal conductivity

According to the results, the thermal conductivity of ETGL is by 1,16 WM-1.K-1. No comparable data could be found in the literature except Minke's work. He summarized the thermal conductivity of lightweight loam and solid loam compared to various specific weights. The result obtained from this study is plotted together with Minke's graph in Figure 73.

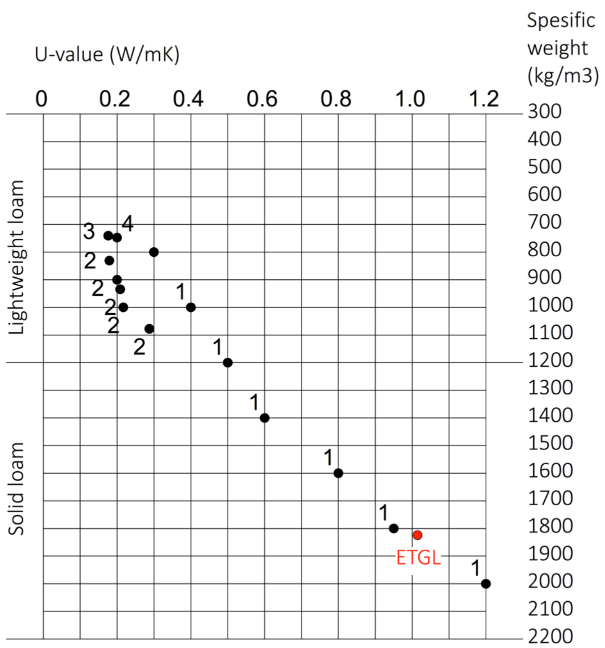

Figure 72: Thermal conductivity of different loams and ETGL (adapted from Minke 2013 [48]*)*

The bulk density of the plain earth used for the experiments is by 2,11 g/cm^3. According to the graph earth with 2,11 g/cm^3 density has a thermal conductivity of about 1,2 WM-1.K-1. The obtained result shows that the TGL stabilization lightly decreases the thermal conductivity of earth.

As can be seen from the graph, the U-value of ETGL is quite higher than of lightweight earth. Experiments focused on using shaw dust or straw with ETGL to improve the U-value may be beneficial.

5.1.8 Summary of mechanical product performances

Results have shown that the SP of earth with trass, gypsum, and lime (ETGL) is 4 times higher than plain earth. ETGL shows 80% less shrinkage than of plain earth. 10 minutes of a water saturation test has shown that ETGL is 99,95% insoluble in water, whereas plain earth has lost 38,5% of the mass. Moreover, FTC did not show an erosive effect on ETGL specimens. According to the results the mix-design with the most promising SP has a final setting of 14,75h. This time can be retarded when a retarder such as CA is added to the mixture. XRD analyses could prove the water-insoluble compounds as a result of pozzolanic reactions. These compounds are responsible for the higher durability and strength of developed stabilized earth mixture.

Furthermore, the properties of ETGL with 20% water addition can be summarized as given in Table 30 below. The average values given in the table are based on values obtained from mix-designs T10G8L2,5, T14G4L2,5 and T16G2L2,6.

Table 30: Properties of ETGL with 20% water

Bulk density (g/cm^3)	1,69-1,86
Flexural strength (MPa), 28d	0,15-0,30
Compressive strength (MPa), 28d	2,5-6
Shrinkage (%), 56d	0,39-0,65
Capillary water absorption	with increased trass content lower
Setting time (h)	0,28-14,75
Thermal conductivity	ca. 1,16

As discussed under the chapter 2.4.4, Wild et al., Lopez et al., Jha et al and Gadouri et al. did investigations on expansive soils stabilized with pozzolana, gypsum and lime in different mix-design combinations. Finally, a comparison of the results obtained in this study with the related studies done by other researchers is tabularly summarized in Table 31 below.

Table 31: Tabularly comparison of the results obtained from pozzolana, gypsum and lime stabilizations

Related study	Mix-design	CS (MPa)	Expansion	Shrinkage (%)	XRD	Notes
Lopez[46] et. al, 2011	expansive soil + fly ash (15%) + gypsum (10%) + lime (2%) water 20%	1,75	-	-	Ettringite CSH[47]	-
Wild[48] et al. 1995	kaolin clay with slag (4-8%), lime (6-2%), gypsum (4%) (total additive 14%)	-	Ca. 10% (L6G4) Ca. 0.26% (L6G4GGBS 4)	-	-	-
Jha[49] et al. 2016	Very expansive soil with fly-ash (10%), lime (2%,4%,6%), gypsum (1%)	-			Ettringit, CASHH[50], CSH	The soil-fly ash, lime, gypsum do not exhibit any swell in the compacted specimens. cementitious compounds block the migration of ions and water into pores/voids, leading to a reduction of ettringite formation.
Gadouri[51] et al. 2019	Expansive and non-expansive soil with natural pozzolan (10%, 20%), lime (4%, 8%), gypsum (2%,4%,6%). Max. total additives 30%	-	-	-	Ettringite CSH	They focused on cohesive character of improved soil and shear strength.
Cicek et al. 2020	Non expansive industrial clay + sand with trass (0-16%), gypsum (2-10%), lime (1,5% to 2,5%). Max. total additives 20,5%	2,5-8,6 (dry) 1,5-2,5 (wet)	0,05-0,30 (by FTC)	0,39-0,65	Ettringite	XRD-analysis was used to determine the reaction products. Further methods are needed to comprehensively investigate the mineralogy of the mixtures

[46] Lopez et al. “Effect of fly ash and hemihydrate gypsum on the properties of unfired compressed clay bricks” 2011.

[47] calcium silicate hydrate

[48] Wild et al. “Effects of ground granulated blast furnace slag (GGBS) on the strength and swelling properties of lime-stabilized kaolinite in the presence of sulphates” 1995

[49] Jha et al. “Gypsum-Induced Volume Change Behaviour of Stabilized Expansive Soil with Fly Ash-Lime” 2016

[50] calcium aluminum silicate hydroxide hydrate

[51] Gadouri et al. “Effect of the interaction between calcium sulphate and mineral additives on shear strength parameters of clayey soils” 2019

5.2 Environmental performance of ETGL

5.2.1 CO_2 emissions of ETGL

Reducing energy consumption and environmental planning are some of the greatest challenges for architects. In this context, the construction industry receives the greatest attention. Hence, the construction industry is a large contributor to CO_2 emissions, with buildings responsible for 40% of the total European energy consumption and a third of CO_2 emissions [138] [139]. One of the corresponding EU targets for sustainable growth is the reducing greenhouse gas emissions by 20% compared to 1990 levels by 2020 [138]. In respect to the EU target, ETGL aims to replace the use of cement in earth stabilization and therefore, to reduce the cement-related CO_2 emission.

In this study, the CO_2 emission calculation is done according to life cycles modules A1-A3, which contain the production of the material as described in EN 15804. It is also called “from cradle to gate” including the considerations about raw materials and fuel supply, as well as transport and manufacturing processes.

Due to the needed high temperature during the burning process, the highest CO_2-emitting additive used in this study is lime. In comparison to lime, gypsum can be produced by low temperatures (calcination requires 125 °C [62]). Results have shown that in between the mix-designs used for development tests T16G2L2,5 has shown the best strength and durability performance. Therefore, T16G2L2,5 has been used as a mix-design reference for carbon-footprint calculations.

To compare the performance of T16G2L2,5 with cement stabilized earth, the CO_2-emitting additives of ETGL (gypsum and lime) were substituted with an equal amount of cement. The amount of gypsum and lime in T16G2L2,5 is 4,5% (2% gypsum + 2,5% lime). Therefore, 4,5% of cement was used as a substitution. This mix-design was then labelled as T16C4,5.

Moreover, the earth with only cement addition was labelled as C10. The mix-design C10 is an assumption based on literary research. According to the summarized results as can be seen in chapter 5.1.2 and Table 28 having earth with 6 MPa CS value around 10% cement is necessary.

A CO_2 emission calculation has been done according to 100kg dry mix design consisting of the additives given in Table 32.

Table 32: Mix-design combinations and the amount of additives for 100 kg mix-design

Labelling	Dry mix-design (kg)	Additives (kg)				Earth (kg)	
		Trass	Gypsum	Lime	Cement	Clay	Sand
T16G2L2,5	100,0	13,3	1,7	2,1	0,0	24,9	58,1
T16G3L1,5	100,0	13,3	2,5	1,2	0,0	24,9	58,1
T16L4,5	100,0	13,3	0,0	3,7	0,0	24,9	58,1
T16C4,5	100,0	13,3	0,0	0,0	3,7	24,9	58,1
C10	100,0	0,0	0,0	0,0	9,1	27,3	63,6

The CO_2 emissions of particular additives used in this calculation were obtained from ProBas Umweltbundesamt[52] [140]. These values are as follow:

- CO_2 emissions of trass 27,9 $kgCO_2$/ton [141]
- CO_2 emissions of gypsum 1,64 $kgCO_2$/ton [142]
- CO_2 emissions of lime 736 $kgCO_2$/ton [143]
- CO_2 emissions of cement 735 $kgCO_2$/ton [144]

Hence, the calculated CO_2 emissions of mix-designs with particular additives in 100 kg of dry mix-design is given in Table 33.

Table 33: CO_2 emission of particular additives in 100 kg dry mix-design

	CO2 emissions in 100 kg of mix-design				
additive	trass	gypsum	lime	cement	total CO_2 emissions
Mix-design	kg	kg	kg	kg	kg
T16G2L2,5	0,37107	0,002788	1,544972	0	1,9188301
T16G3L1,5	0,37107	0,0041	0,8832	0	1,25837
T16L4,5	0,37107	0	2,7232	0	3,09427
T16C4,5	0,37107	0	0	2,7195	3,09057
C10	0	0	0	6,6885	6,6885

Finally, the compilation of strength performance and the CO_2 emissions of mix-designs given in Table 32 are plotted in Figure 73 below.

[52] The German Environment Agency (UBA)

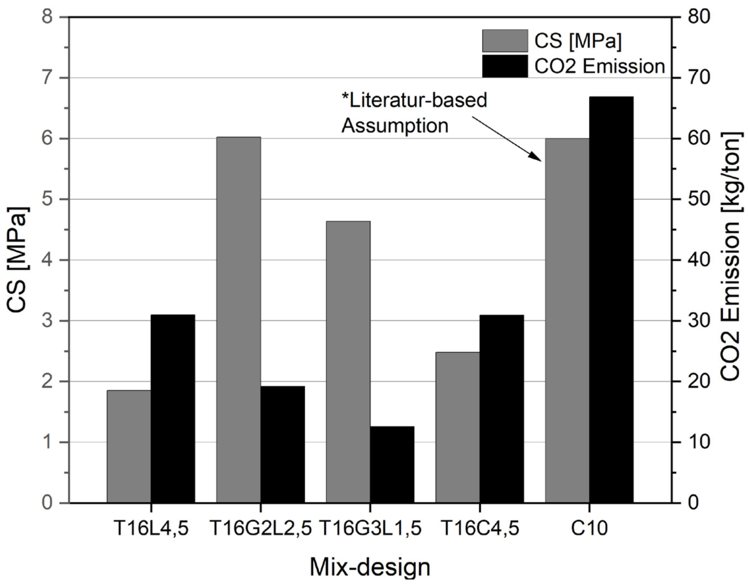

Figure 73: CO_2 emissions of ETGL compared to earth+cement

According to the results, although T16G3L1,5 has the lowest CO_2 emission, T16G2L2,5 compared to all other mix-designs possesses the best CS/CO_2-emission relationship. Using 4,5% cement, on one hand, causes a dramatic decrease in CS, on the other hand, environmental impact increases. Although with 10% cement 6 MPa CS can be achieved, this causes a significant increase in CO_2 emission, with other words, CO_2 emission compared to reference mix (T16G2L2,5) tripled.

The CO_2 emission calculation, with the reference mix-design T16G2L2,5, has shown that earth stabilization with TGL compared to cement stabilization, can significantly reduce the environmental impact by increasing the strength and durability of the earth. ETGL is about 72% more environmentally friendly than the cement stabilized earth. Moreover, the mix-design T16G3L1,5 has shown that by reducing the lime content from 2,5% to 1,5%, the environmental impact can further be reduced, while still having an ETGL with a CS of 4,64 MPa.

The CO_2 emission calculation done in this study is based on values obtained from ProBas Umweltbundesamt. However, especially CO_2 emission values of cement significantly differ from source to source. Latawiec et al. stated that clinker emission factor equals to 897 kg/t for Europe and US [145] [146]. They also stated that superplasticizers cause a great amount of CO_2 emission, but they are being eliminated by CO_2 emission calculation of cement. Also, Kaid et al. 2015 for instance used a value of 11kg/ton CO_2 emission for natural pozzolan and 914 kg/t CO_2 emission [147] for cement. Hence, the environmental performance of ETGL may even be better than the results obtained from this study.

5.2.2 Recyclability

ETGL is composed of the industrial earth (clay+sand) with trass, gypsum, and lime addition. Earth walls, adobe bricks, compressed earth blocks, mortars etc. made of ETGL mixture can be demolished, ground, and reused. By adding clay with the same stabilizing agents or by only adding the stabilizing agents into the grounded waste ETGL, the new mixture can be reused for the manufacturing of stabilized earth materials such as stabilized earth blocks and wall elements etc. Finally, the life cycle of a building material made of ETGL can be described as shown in Figure 74.

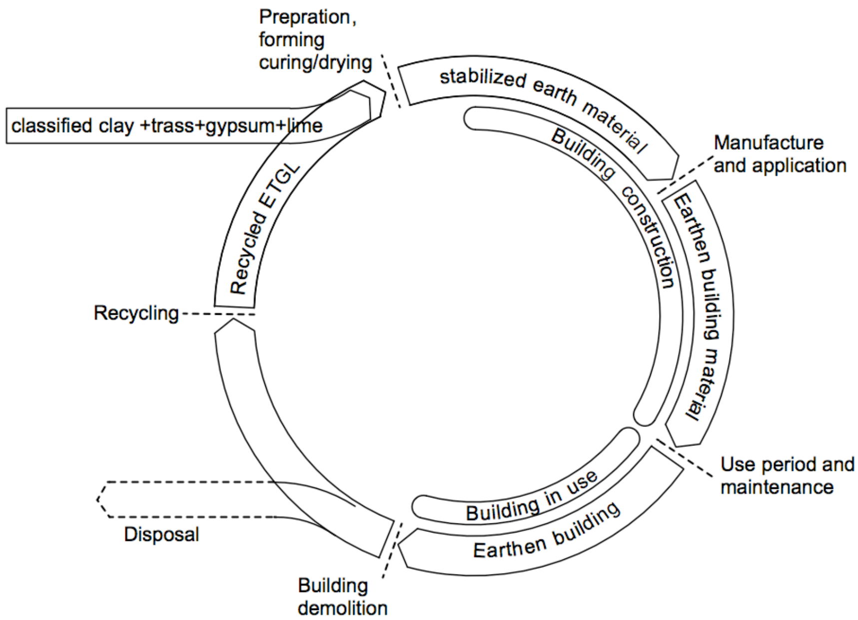

Figure 74: Building with stabilized earth presented as self-sustaining life cycle. Graph adapted from [12]

The additives trass, gypsum and lime cannot be filtered out from the stabilized earth material. However, for instance additional reinforcement products such as jute or glass fibres used with ETGL can be easily separated from the stabilized earth product. To demonstrate the recyclability, a stabilized earth specimen with natural jute fibre was produced. The specimen was left to dry over 3 years and then crushed. As can be seen in Figure 75 ETGL product can easily be crashed, grounded and reused.

Figure 75: Recycling an ETGL product dried over 3 years

Trass, gypsum, and lime were added to the recycled ETGL and 20% water was added to the dry mix. The wet mixture was used to produce a recycled and re-stabilized specimen as shown in Figure 76.

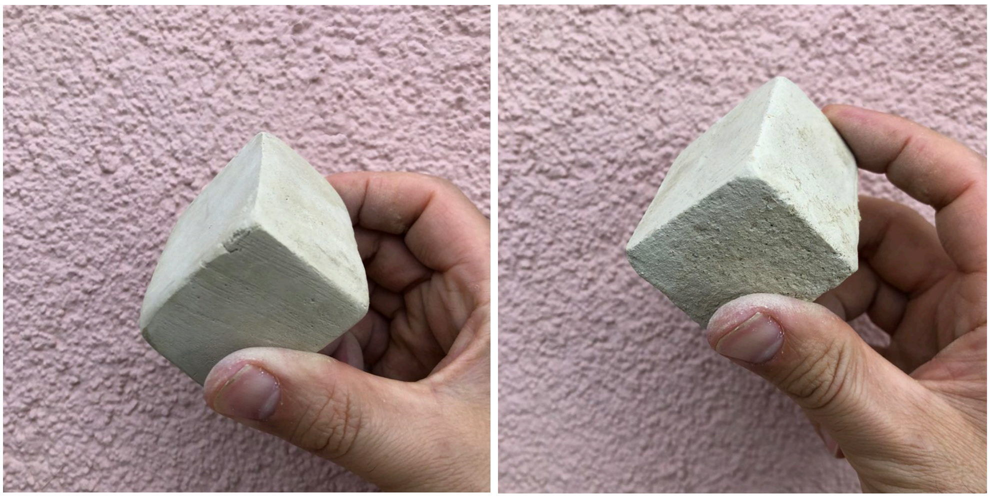

Figure 76: recycled and re-stabilized earth specimens. Recycled ETGL stabilized with kaolin clay, trass, gypsum, and lime (left). Recycled ETGL stabilized with trass, gypsum, and lime (Right).

The recycled ETGL can either be stabilized just by adding the same additives or with same additives and extra clay addition.

5.3 Workability of the ETGL

In this chapter, the potential of the developed earth mixture with trass, gypsum, and lime (ETGL) has been discussed and a proposal for its application in the field of construction has been created.

5.3.1 Workability (slump) test

Three different mix-design combinations were used for the slump test. The labelling and mix-design proportions can be seen in Table 34. In all mixtures the water content was 20 wt% of total dry mix consisting of earth and additives. The slump mould and its dimension are shown in Appendix N.

Table 34: Labelling and mix-design proportions used for slump test

Labelling	T10G8	T14G4	T16G2
Description	earth with 10wt% trass, 8wt% of gypsum and 2.5wt% of lime	earth with 14wt% trass, 4wt% of gypsum and 2.5wt% of lime	earth with 16wt% trass, 2wt% of gypsum and 2.5wt% of lime

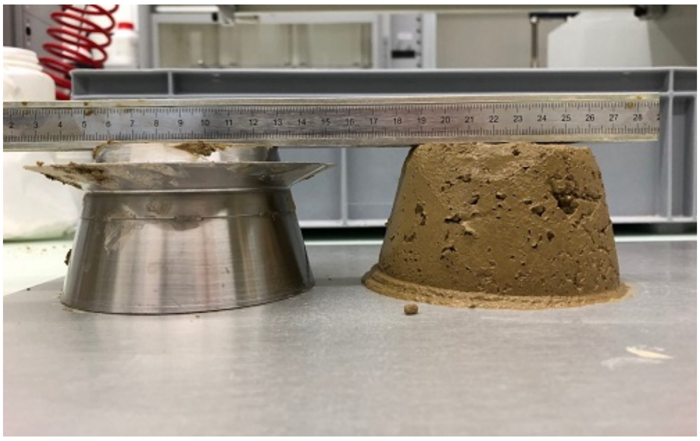

Figure 77: Slump test

Four types of slump are defined in the literature, and these can be seen in Figure 78 below.

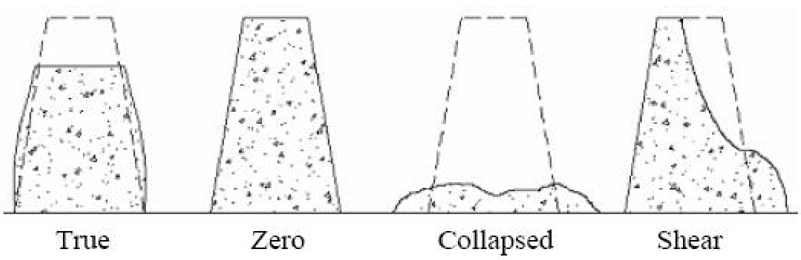

Figure 78: Four types of slump [84]

According to the slump types, all stabilized earth mixtures showed almost a zero slump. The measured very minimal slump values are given in in Table 35.

Table 35: The results of slump test different mix-designs

Specimen	Slump (mm)
T16G2	3
T14G4	2
T10G8	1

The relationship between gypsum content and slump value is plotted in the graph shown in Figure 79. As can be seen in the graph, with the increasing amount of gypsum the slump value of the mixture decreases. This is due to the effect of the rapid hydration of gypsum.

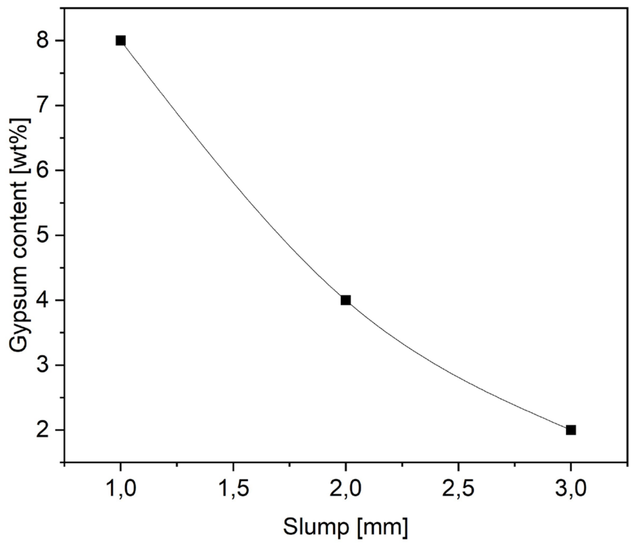

Figure 79: Relation between slump value to gypsum content

5.3.2 Mixture and consistency

Depending on water content and clay content, various mixture qualities can be produced. Figure 80 presents a summary of different water and clay content in the ETGL mixture and their general limits recorded during experimental study.

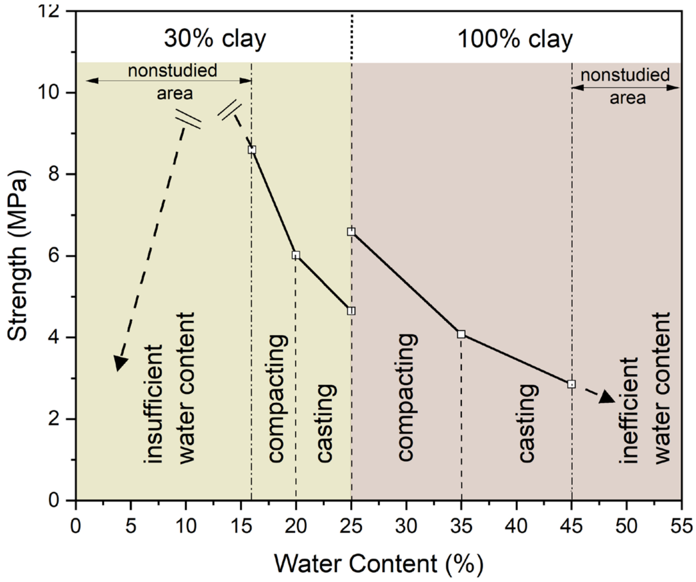

Figure 80: Summary of effect of clay and water content on material performance and character of stabilized earth

Water content below 15 wt% was insufficient to manually compact the ETGL mixture. While 15 to 20 wt% water was sufficient to produce a compactable mixture, 20 to 25 wt% water enabled a castable mixture without the need of compaction. Moreover, if the earth consisted of 100% clay, then a minimum of 25% of water was needed to compact the ETGL mixture. Up to 35% of a water ETGL mixture with 100% clay reaches to a castable consistency, however, 45% of water was the upper limit for an acceptable casting (see Figure 81).

Figure 81: ETGL with 100% clay and 25%, 35%, and 45% of water addition

One disadvantage of having very high clay content in the mixture is the significant increase in water consumption. If 30% of the earth consists of 30% clay as used in this study, 20% of water is enough to produce a castable mixture without any need on compaction. By using 100% clay, the amount of water needed for a castable mixture increases up to 45%.

5.3.3 Summary

The SP, the consistency depending on production method, and surface quality of the ETGL can be controlled as mentioned in the previous chapter through water content or grain size. ETGL can potentially be produced as a dry-mix, which can be used for different purposes and types of application. Mortars, blocks, panels, plasters or compressed massive wall elements can potentially be produced with the developed ETGL mixture.

5.4 Market application and usability of ETGL

Today a great variety of materials made of unfired and/or stabilized earth are available on the market. These materials are listed in

Table 36.

Table 36: Unfired earth products and building elements available on the market.

Unfired earth materials and building elements available on the market	
Non-Stabilized earth products and building elements	**Stabilized earth products and building elements**
Adobe	Stabilized adobe
Compressed earth blocks (CEBs)	Stabilized-CEBs
Rammed earth wall	Stabilized-rammed earth walls
Earth plasters and mortars	Stabilized- earth plasters and mortars
Earthen boards and panels	-**No product available yet**-

ETGL mixture can be used for the production of any of above-mentioned building materials offering a significantly improved SP and water-resistance.

In-between all unfired earthen materials drywall system with earthen panels is gaining remarkable interest. The desire for short and efficient construction times in the last decades has increasingly attracted drywall construction materials and techniques into the building industry. Earthen panels are greatly favoured today as a drywall system for interior planning. Especially in Germany, earthen panels are produced and installed as drywall systems by many manufacturers.
Therefore, the following chapter the state of the art is limited with earthen panels and boards.

5.4.1 Application

In Germany, the earth material is now moving in a direction, so that it is no more only material of a load-bearing system or a type of construction, but it has become a material, which can also be integrated with any different structural system as a building element. There are currently more than 30 companies (Claytec, Lehmorage, Procrea, Conluto etc.) that manufacture their products using special shaping technologies. These prefabricated panels are supplied with all the necessary clay plaster layers.

This chapter provides an overview of the terms, formats, composition and intended uses of the existing clay boards.

5.4.1.1 The term “clay panel” and standards

Clay panels are designated by Dachverband Lehm e.V[53] as plate-shaped building materials. Today, however, bent (rounding) panels are also produced. In addition, these existing clay panels have very different dimensions and are not regulated. Soils with a density of less than 1200 kg/m^3 can also be referred to as lightweight panels [148]. However, some manufacturers classify their products as light and heavy clay boards or as clay elements. In December 2018 DIN published a new earth building standard called DIN 18948 [149] Earthen Boards Requirements, Test and Labelling. This is the first very comprehensive standard related to the earth boards and panels used as a component of a drywall system.

5.4.1.2 Thickness and size of the clay panels:

There are many non-standard clay panels on the market. The panel’s thickness depends on the intended use. Concerning the dimensions, a defined boundary is not known.

The thin clay panels are of the order of the dimensions of conventional drywall boards. They normally require a substructure. The thick clay panels are block-like formats with transition to stone formats [148]. Strong panels are prefabricated in large formats and are self-supporting like thick clay panels. The clay panel formats, which have a smooth transition between the clay panels and adobe bricks, are referred to as clay elements.

[53] Dachverband Lehm e.V: As an association of interests for all those who work and live with clay, the "umbrella organization Lehm e.V." was founded in 1992 with the aim of promoting this future-oriented building material. (http://www.dachverband-lehm.de/verband/ (Accessed 16.10.17)

Table 37: Clay board classes with the different types of use (adapted from Schröder 2014) [29]

Classes	Thickness (mm)	Current Sizes (mm)	Type of use
(I) Thin panels	12,5	250x1200	a) Covering the interior construction elements (suspended ceilings, attic floors, Raster-constructions, non-load bearing separator walls) c) Cladding of planar sub-surfaces (concrete and Limestone walls, old plastered surface, Wooden elements, composite wood panels) c) Dry-screed boards in floor construction d) Formwork for multi-layered wall constructions e) Wall heating and cooling*
	14	450x900, 625x1250	
	15	1250x1500, 1250x2500	
	16	280x1250, 625x1000, 625x1250	
	20	244x1250, 625x1500	
	22	625x1000, 625x1250	
	25	250x1200, 250x1250, 600x1200, 625x800*,625x1000*,625x 1600*, 625x2000*	
	30	244x1250	
	35	250x1250, 250x1250*, 300x1000, 295x1350, 295x125*	
	50	250x1250	
(II) Thick panels	51-125	250x520, 250x260, 295x850, 240x1000, 245x1000, 500x500, 850x295, 920x295, 1000x295*	a) Self-supporting separating walls b) Infill for roof slopes c) Floor panels/tiles d) Integrated heating pipes e) Clay Hypocausts* f) Hollow panels
(III) Strong panels	250-450	Depends on planning	a) Load-bearing interior and exterior walls

5.4.1.3 Application of the clay panels:

Clay panels are used for interior walls, prefabricated shells, suspended ceilings, and attic flooring. They are used for the planking of grid constructions or are glued as dry plaster on flat surfaces. These include concrete and limestone walls, old plaster surfaces as well as solid wood components and wood-based panels [150].

Thin clay boards are used for cladding and drywall system. They are joint with each other. Thick clay panels are used for non-load-bearing partition walls without a substructure, also as infill for roof slopes or ceiling-infill for slabs. They are laid like bricks. Strong clay boards are produced as ceiling-infill or as prefabricated large-format wall slabs made of rammed earth for load-bearing wall constructions. Besides, some clay panels are produced especially for the installation of wall heaters or as hypocaust-elements [150] for wall-heating systems. A clay board with integrated heating pipe is shown in Figure 82.

Figure 82: Clay boards with integrated heating pipes [151]

Detailed information on clay panels and boards published by Röhlen and Ziegert 2014, Volhard 2016 [152], and Schröder 2010 [148].

5.4.1.4 Preparation and forming:

Clay boards are completely prefabricated with the help of special technologies of forming and supplied with standard transport means. There are currently various methods of manufacture. Conventional processes are the extrusion, single-press, injection process or belt production. Clay boards can also be manually manufactured locally in suitable processes [148]. For laying as bricks, the panels are produced in different formats with a circumferential tongue and groove profile. In the case of thin clay plates, special belt presses are used, whereas thick clay plates can usually be produced by extrusion or by other methods of more elementary shaping. In the last decade, using prefabricated large-format wall elements has been especially popular. Companies produce these wall elements either in their own production halls or at the construction site, equipping the construction site with necessary equipment. The large wall elements are prefabricated by means of rammed earth method and with the aid of suitable formwork systems. In Figure 83 such kinds of large-wall elements can be seen, which were produced at the construction site.

Figure 83: Riccola production centre Switzerland. Architects: Herzog &De Mereuon. Planning and production of rammed earth blocks by Firm "Lehm Ton Erde" from Austria.[54]

[54] DETAIL Zeitschrift für Architektur Review of Architecture 55. Serie 2015-3 Industriebau; S. 217

5.4.1.5 Colour as a design parameter

All ingredients of the earth mix have effect on the final colour of the product. Therefore, a wide range of colours can be achieved simply through the colouring of binders, aggregates, and other additives [17]. Today there is a significant market based on natural earth colours produced by different types of earth powders (see a colour plate by clayfix in Figure 84).

Figure 84: Colour plate of earth colours[55]

Fromme & Herz 2016 have comprehensively discussed the subject design of earth surfaces, earth colours and optic in the book Lehm- und Kalkputze.

5.4.1.6 Deficits of earthen panels on the market:

The deficits of the earthen panels available on the market can be drawn up as follows:

- They are designed only as an infill or a plaster-base material.
- they need to be subsequently plastered (undercoat and finish layer), which is both time-consuming and costly because of the workmanship and curing time.
- the curing time is up to two to three weeks in good weather conditions.
- They are soluble in presence of water if not sealed with water repellent materials.

[55] http://www.parkett-naturbaustoffe.de/content/Lehmfarbe-Lehmputz.html

5.4.1.7 Summary

In Europe, Germany possibly has the most successful market in Europe for earth construction products, with an annual turnover of £60 million and a sustained growth of 20% per annum at a time when the rest of the construction industry experienced no growth (Schroeder, 2000) [153]. As mentioned on the table above earthen panels and boards with different functions such as with integrated heating pipelines etc. are being used in interior architecture. However, since now stabilized earthen panels have not been appeared on the market.

In this respect, ETGL can be a significant alternative, which can be used in the field to overcome above-mentioned deficits. This has the potential to open a new avenue in the growing earth construction sector. For this reason, a proposal has been created in the following chapter.

5.4.2 A proposal for using ETGL

In this chapter, a proposal has been discussed based on using ETGL mixture for production of a stabilized earth panel (SEP).

As mentioned in chapter 5.4 there is yet no stabilized earthen panel available on the market. The existing earthen panels are designed to be only a component of the earthen drywall system and need to be plastered after installation to obtain the final optic and haptic. However, this proposal is based on a SEP, which is manufactured to be an interior product with the final optic and haptic. The main advantages of the proposed SEP are as follow:

- A completely prefabricated unfired and stabilized earth-based interior product.
- They do not need plastering, painting, or curing time after installation. Therefore, there is a short construction process.
- They have higher durability and strength in comparison to existing earthen panels.
- Since they are already dry, shrinkage only occurs in joints [48].

A detailed section drawing showing the principle of integrating the stabilized earth mixture with the wooden framework is shown in Figure 85.

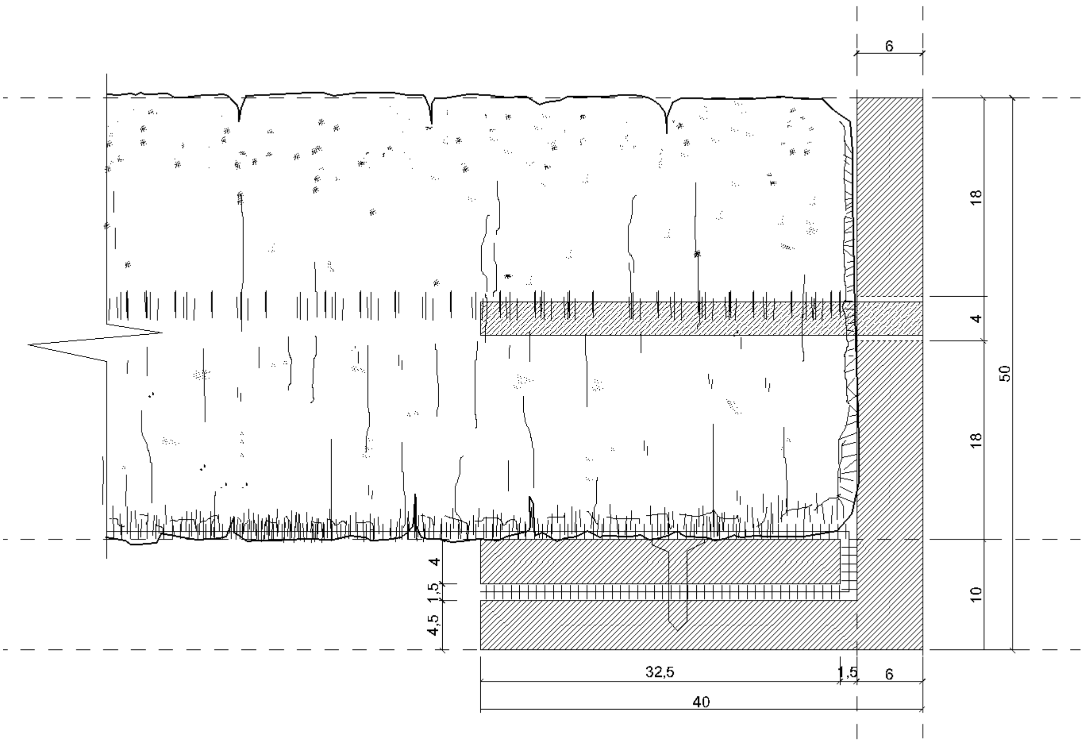

Figure 85: Section of stabilized earthen panel integrated to the wooden framework through jute fibres and lateral wood stick.

The summary of the manual preparation steps of SEP can be seen in Figure 86 below.

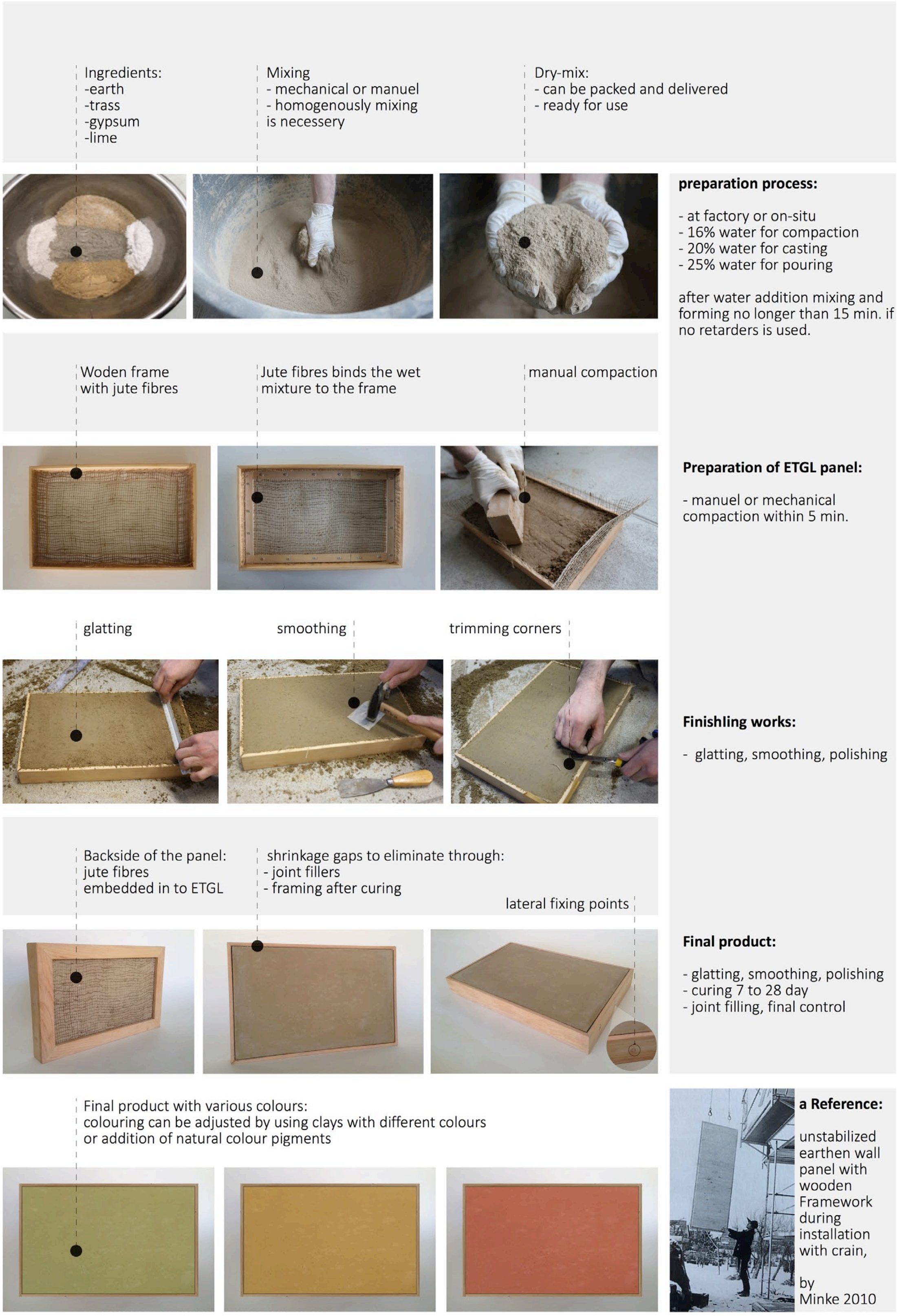

Figure 86: A proposal: preparation of a stabilized earthen panel with ETGL

Preparation

Earth and additives (trass, gypsum, and lime) were mixed until a homogenous dry mix was ensured. After adding 16% water into the dry mixture, the mixing process was completed in three minutes. Wet mixture was then immediately filled into the wooden frame in layers. The layers were compacted carefully. Compacting was finished in 10 minutes. Following this the surface was flattened and smoothed. Finally, the corners were trimmed to have a proper optic and the mock-up was left to dry.

For industrial manufacturing, the existing technologies used in the field of earthen panel production process are suitable. As mentioned in chapter 5.4.1.4 conventional manufacturing processes such as

- single press (suitable mixture: ETGL with 16% water),
- extrusion (suitable mixture: ETGL with 20% water), or
- injection process (suitable mixture: ETGL with 25% water) can be used according to the needs and equipment of the manufacturer.

Framing concept

Minke 2013, has stated that a German company HDB Weissinger produced 1mx3m high timber frame wall elements filled with lightweight loam [48]. Similar to the concept shown by Minke's book Building with Earth, an L-shaped thin wooden profile is being used to edge the stabilized earth. The difference of proposed edging compared to the timber edging planned by HDB can be seen in Figure 87 below.

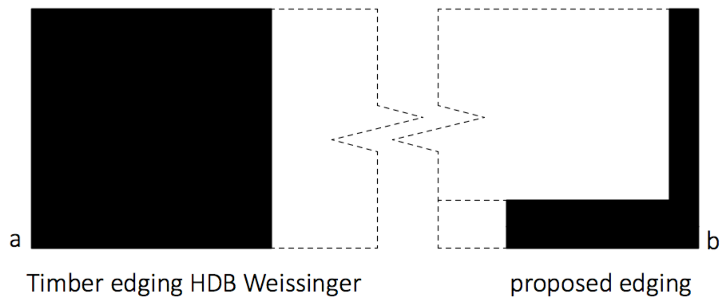

Figure 87: Comparison of the edgings; a- timber edging planned by HDB, b- the proposed edging

According to Minke, panels lighter than 800 kg/m^3 must be edged with timber since their edge strengths are insufficient for handling. Although the density of ETGL is about 1800 kg/m^3 a thin wooden profile is provided, which helps to observe the,

- completion efficiency with a frame
- shrinkage phenomenon after the curing process
- optical effect and
- the integration of frame and ETGL with each other in case framing is necessary.

Binding the earth to the frame

To bind the dried ETGL to the frame a jute fibre is used, which is then stretched and attached to the bottom of the wooden frame. While compacting the wet mixture into the frame, the fibre becomes embedded into the wet earth mixture at the bottom of the frame. After the drying process, the embedded fibre is then bonded to the earth and both ETGL and wooden frame are integrated.

Shrinkage

Shrinkage is observed after the curing process. With the proposed system, the curing process of ETGL takes place within the frame. Therefore, after the completion of curing a 1,5mm gap occurs on four sides of the dry earth. This gap can easily be filled with timber glue as applied after the curing process.

Further needed/critics

- Methods need to be developed to overcome the deformation or damages of the profile while compacting the wet mixture into the wooden profile.
- Alternative solutions need to be developed to overcome the shrinkage phenomenon.
- Another significant phenomenon is the weight of the product. SEP with different sizes and thicknesses need to be produced and tested.
- Performance tests, as mentioned in chapter 3.2.2, need to be conducted to classify the product.

5.4.3 Sanding and surface texture of ETGL

Dried ETGL specimens can easily be sanded independent of the mix-design combination as can be seen in Figure 88. For sanding different types of machines can be applied as presented in the figures below.

Figure 88: sanding experiments on SES with different machines

Various surface qualities from smooth to raw surfaces can be rendered by controlling the grain size of the sand added to the earth. Figure 89 presents sanded ETGL specimens with grain sizes from 0,5 to 2mm.

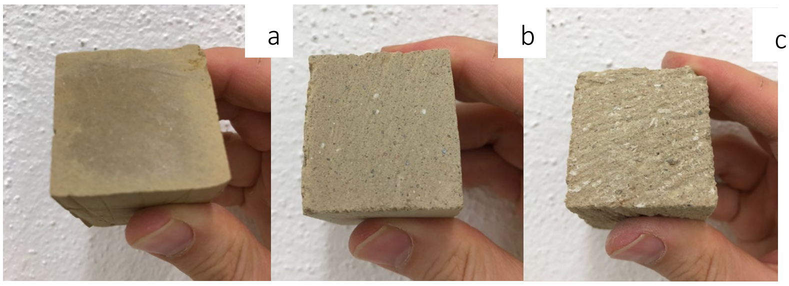

Figure 89: sanded specimens with different grain size distribution, a- grain size 0,5mm, b-grain size 1mm, c- grain size>2mm

Another method to render different surface optics can be achieved by controlling the water content as presented in Figure 90.

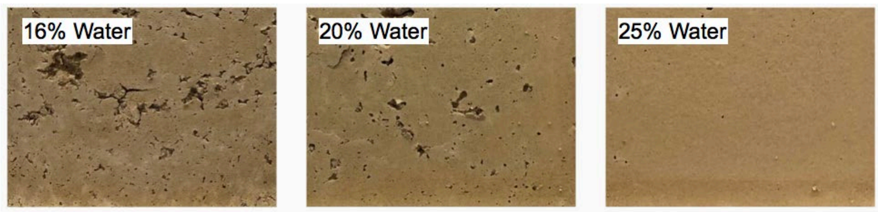

Figure 90: Different surface renders controlled by water content

However, it is important to note that the more water is added, the less the SP. Water content versus strength performance was discussed under chapter 4.1.1.

5.4.4 Cutting of ETGL

Cutting experiments were conducted on ETGL material. Results have shown that ETGL can simply be cut by using appropriate cutting equipment. An important phenomenon is the generation of dust while cutting materials at a construction site or factory. ETGL withstands also wet-cutting condition, and the material does not dissolve by exposure to water as is shown in Figure 91.

Figure 91: wet-cutting experiment on stabilized earth specimens.

6 Conclusion and outlook

6.1 Conclusion

The method developed in this study allows for the stabilization of earth with the vernacular binder trass, gypsum, and lime (TGL). This environmentally friendly binder is inspired by vernacular stabilization but revisited knowing the potentials of cement.

The main result is that earth stabilization by using TGL significantly improves the strength performance and durability of plain earth (PE). ETGL is water-insoluble and can withstand the freeze-thaw cycles. Thus, the two most critical drawbacks of PE, moderate strength and low water stability as mentioned in the introduction of the study, have been overcome. Where the CS of PE is about 1,5 MPa ETGL has a CS of over 8,5 MPa. This value is 4 times higher than the value as required by standards (2MPa). Even the wet CS with about 2,5 MPa, is above the required value. The improvement in strength and durability is due to pozzolanic reaction products. One of these products is ettringite, which could be identified by XRD analyses. With the increasing amount of trass, the precipitation of ettringite was increased. This provokes the progressive improvement of the compressive strength of ETGL. Also, apart from improving the load-bearing capacity of earthen a great advantage of TGL stabilization is that the surface hardness and edge strength of the material is being improved so that the demoulding is possible after only one day. This significantly accelerates the production and completion processes. Because the initial setting of ETGL is about 20 min, the final setting is about 15 hours. When compared with gypsum or cement stabilization, this time is sufficient for comfortable workability. One important phenomenon is shrinkage of earthen materials. It is not only an obstacle for better material strength but also for precise and smooth planning. ETGL has a remarkably reduced shrinkage value over PE. This allows architects to render smooth surfaces and to have good material workability.

Another challenge of the proposed stabilization was reducing the environmental impact. When compared with Portland cement stabilization, this method is by far a more environmentally friendly way to reduce CO_2 emission. With the TGL stabilization, a reduction in environmental impact of at least 72% could be achieved. Thanks to trass less gypsum (2%) and lime (2,5%) are needed. For instance, a typical gypsum stabilization is efficient when 8-10% gypsum is added, and a typical lime stabilization is efficient when ca. 3-8% lime is added into the earth. It is even possible to reduce to lime content to 1,5% while having a CS of more than 4,5 MPa, which further reduces the environmental impact.

Moreover, trass also allows for avoiding of the use of by-products such as fly-ash or blast-furnace slag in earth stabilization. This further contributes to the environmentally friendly targets, by preventing the encouragement of sectors responsible for the production of by-product.

Furthermore, the method used in this study is the first of its kind that allows for the avoiding of the very time-consuming processes such as finding a suitable source for soil excavation and soil classification. This approach significantly simplifies the earthen building process. Also, the developed mixture has significant workability. We are able to cut, drill or sand ETGL with conventional equipment both in dry and wet condition. Compacting, casting, and pouring is possible, which can be decided according to the needs and type of use. As proposed in this study, the developed mixture is suitable for the production of stabilized earthen panels that are the first of its kind. Such a panel is practically feasible, reasonable, and could be integrated into earthen building standards in general and in particular to DIN 18948, which is related to earthen boards and published in 2018.

6.2 Outlook

The dry ETGL mixture with improved strength and durability allows for the production of not only stabilized earthen panels but also further unfired earthen building materials such as stabilized earth blocks, stabilized plasters, and mortars, stabilized earthen wall elements or stabilized monolithic rammed earth walls etc. In this study only 7day and 28day SP experiments were conducted. However, pozzolanic reactions are long term reactions. Therefore, investigating SP of 56day or 91day cured specimens may provide significant data on strength development of the proposed stabilization. Water content has a significant effect on the performance of earthen materials. Hence, the effect of different water contents on strength performance (SP) of ETGL was investigated. The effect of compaction degrees on SP of ETGL should also be investigated, which will provide essential data, especially for the production of stabilized rammed earth walls. The tests undertaken in this research project were, as mentioned in chapter 3.2.2 Table 4, the development and performance tests related to the stabilized dry-mix. However, more detailed investigations are needed. For instance, ettringite mineral could be identified in cured mix-design specimens thanks to XRD analyses. Together with ettringite, researchers, as given in Table 31, have found other water-insoluble reaction products such as CHS, CASHH in similar admixtures. These, especially alumina containing compounds, may also be present in ETGL. Therefore, other identification technologies could be useful for more specific analyses. Also, the pozzolanicity of the ETGL mixtures should further be investigated. Pozzolanicity can be increased by increasing PH of the mixture. An important role of lime in TGL mix is its role on high PH value. Reducing lime content, while increasing the PH of the mixture in a more environmentally way could be advantageous.

In addition, although ETGL has 94% better shrinkage value than of PE, this is still 3-4 time higher than that of concrete. Probably even for stabilized earth as ETGL the shrinkage is an inevitable phenomenon. Nevertheless, shrinkage of ETGL mixtures should be further and intensively investigated as there is a lack of research on this topic. The aim should be to achieve lower shrinkage values closer to that of concrete. Moreover, as investigated in this study, citric acid retards the setting time of ETGL up to 50 hours. Nevertheless, further experiments with other retarders should be done with respect to effectiveness, costs, and availability.

The first durability tests (water insertion, FTC, and DEF) undertaken in this study have shown that ETGL has a significant potential to withstand extreme conditions. However, as the FTC tests with ETGL were limited with regard to the length change and macroscopical surface observation, further durability tests, including FTC test, rain, and frost erosion tests, are necessary to comprehensively investigate their effect on both strength and microstructural changes.

Moreover, stabilized earth panel (SEP) made of ETGL was produced and discussed as a proposal. Other stabilized earth products made of ETGL, including the proposed SEP, need to be subjected to further performance as well as characterisation tests as mentioned in chapter 2.2.5 Table 2. These tests are, on one hand, necessary to further improve the mixture. But, on the other hand, they are essential for practice to characterize, identify, and classify the new products. The results of performance tests are often provided in the form of datasheets by manufacturers.

Furthermore, compared to other conventional constructions, earthen building costs are usually either equivalent to those or even higher. This is due to laboured workmanship and time-consuming construction times. Also lack of prevalence of earthen building companies, techniques, and workmanship even worsen the situation. Therefore, developing new earthen building techniques and non-fired contemporary earthen building materials will help overcoming the financial aspects and make earthen buildings affordable and attractive.

Finally, the results of this study and those that will be obtained from future studies will open a new avenue for earth stabilization and secure the implementation of this material in the conventional construction industry.

And last but not least, while we nowadays, after every natural disaster, are talking more intensively about environmentally friendly buildings, a challenging parameter will be the CO_2 emission of the products made of ETGL.

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Glossary

Additive	Also used as stabilizer or stabilizing agents, which are being added to plain earth to improve its properties.
Alker	Istanbul Technical University, which has been carrying out research projects on earthen construction material since 1978, has determined that earth can be stabilized with gypsum and lime resulting in improved durability, physical and mechanical properties with a compressive strength of 2-4 N/mm 2. This combination is referred to as "Alker."[80]
Bulk density	Soil bulk density is defined as the ratio of oven-dried mass weight to its bulk volume depends on the soil particles densities such as sand, silt, clay and organic matter and their packing arrangement [154]
Consistency	the relative ease with which a soil can be deformed [155]
Dry density	In order to determine the optimal water content for a given earth sample, a proctor (dry density) test can be applied. In particular, the optimal water content, for which at given level of compression force corresponds maximum densification (that is, reduction of the inter-granular spaces and an increase of the number of contact points between particles) in order to increase the density, reduce the possibility of compaction and increase the cutting resistance [156]
Drywall system	Drywall is the ceiling and wall material used for about 90% of all new home interiors. It is also used frequently for repair or remodelling of plaster walls. Drywall is made from gypsum, and comes in sheets from 4' x 8' to 4' x 16', with a paper coating on both sides.[157]
Ettringite	A highly expansive crystalline mineral. Cement hydration products provide the calcium and alumina to react with sulfates to form ettringite [42]
Fly ash	Fly ash is one of the most plentiful and versatile of the industrial by-products (Collins and Chiesielski 1992). It is generated in vast quantities (more than 65 million metric tons per year) as a by-product of burning coal at electric power plants [158]
Loam	Earth, when used as a building material, is often given different names. Referred to in scientific terms as loam, it is a mixture of clay, silt (very fine sand), sand, and occasionally lager aggregates such as gravel or stones [48]
Plasticity	Plasticity refers to a soil's ability to deform without cracking or disintegrating. It is important in earth construction because it reveals the ease of shaping the soil and the sensitivity of the soil to variations in humidity [16]
Porosity:	Porosity ϕ is the fraction of the total soil volume that is taken up by the pore space. Thus, it is a single-value quantification of the amount of space available to fluid within a specific body of soil [135]
Pozzolana	Pozzolans are defined as siliceous or siliceous and alumnus materials in which in themselves have little or no cementitious property but in a finely divided form and in the presence of water will react chemically with calcium hydroxide at room

	temperature to form compounds having cementitious properties (Neduko et al. 2015) [159]
Pozzolanic reaction	Pozzolanic reaction is a secondary process of soil stabilization. One prerequisite for the formation of additional cementing materials is the solution of silica and alumina from clay components. The high pH environment of a soil cement system increases the solubility and reactivity of the silica and alumina present in clay particles. The degree of the crystallinity of the minerals and particle size distribution are some factors influencing solubility. It is postulated that calcium ions combine with silica and alumina dissolved from the clay lattice to form additional cementitious material (C-S-H and C-A-H) [42]
Thermal conductivity	Thermal conductivity is defined as the time rate of steady heat flow, watts, through a unit area, m^2, per unit temperature gradient in the direction perpendicular to an isothermal surface, "expressed as W/m.k (watts per meter kelvin) [160]

Summary

Earth has been used as a construction material since ancient times. Due to its major drawbacks such as low water stability and moderate strength, the plain earth has been stabilized. Lime, pozzolan or gypsum have been the most used additives for stabilization. Recently, cement has become the most commonly used additive as it improves the strength and durability of plain earth. However, the production of cement causes high greenhouse gas emissions. Using cement as an additive greatly reduces the environmental advantages of earth. Alternatives to cement stabilization are currently neither an additive efficient enough to reduce the CO_2-emission nor allow for the obtaining of better strength and durability performance than that of cement. Therefore, this thesis deals with the rediscovery of a vernacular engineering approach for a low environmental impact earth stabilization technique, aiming to replace cement in earth stabilization. The main research question related to the research objective is:

How can vernacular additives be combined to enable an environmentally and structurally efficient stabilization that allows for the replacement of cement in earth stabilization?

The following sub-questions can be derived from the main question:

Chapter 2: With respect to earthen building standards, which types of soils are suitable for earthen buildings and why is earth stabilization needed?

Chapter 3: What are the main material and investigation-based characteristics of the methodology related to the proposed stabilization?

Chapter 4: Can an associate use of trass, gypsum and lime as an additive serve as a structurally efficient and environmentally friendly form of earth stabilization?

Chapter 5: Which improvements are achieved over relevant studies and what are the advantages of using this mixture when compared to conventional alternatives?

The following summaries describe the key findings for each of the four chapters.

Review of State of the Art (Chapter 2):

The first step in the method consists of a comprehensive review of earth stabilization (ES) with regards to earthen building standards and soil classification. The main findings are as follow:

Cement, lime, fly ash (an artificial pozzolan) and gypsum are common stabilizers, but cement stabilization is the most commonly used, standardized, and addressed in the reviewed literature as it significantly improves the strength and the durability of earth. There is no uniform classification, testing methodology or determination of the types of stabilizers and their limitations of use. Mostly cement testing standards are being used in the field. However, cement in ES is due to its CO_2 emission disadvantages. This is the main research gap.

Mostly, locally excavated and expansive soil types have been used in the research studies. This requires the classification and identification of the soil. This is the second research gap.

According to the review, lime-pozzolan-gypsum combination can be a significant alternative to replace cement in ES. However, only a few studies have been done using artificial pozzolana. Artificial pozzolana indirectly contributes to CO_2 emissions and does not always efficiently improve the properties of earth. This is the third research gap.

In addition, no performance tests (such as freeze-thaw cycle, water resistance, wet compressive strength etc.) were conducted in these studies.

Development of Mix-design (Chapter 3):

In this chapter, the methodology, including the experimental materials and their percentages, is described in detail. The key concept for the development is to combine vernacular additives both to improve the strength and durability of plain earth and to reduce the CO_2 emissions. The earth needed for experiments was made under laboratory conditions, consisting of industrial clay and industrial standardized sand. The industrial earth made it possible to eliminate soil excavation and classification as well as soil suitability tests. The additives used in this study are classified as traditional additives available on the market.

28 earth-mixtures with varying additive contents were prepared and both development and performance tests were done to investigate the performance of this technique. Table 38 shows the tests conducted.

Table 38:The experimental test carried out in this study.

Tests	
Development	Performance
- Slump, - Grain size distribution, - Sedimentation, - Bulk density, - Porosity, - Wet compressive strength, - Dry compressive strength, - Flexural strength, - Dry shrinkage, - X Ray diffraction analyses,	- Wet compressive strength, - Dry compressive strength, - Capillary water rise, - Water erosion, - Water absorption, - Freeze-thaw cycle, - Dry Shrinkage, - Delayed Ettringite formation, - VICAT setting time, - Thermal conductivity

Experimental Results (Chapter 4):

The development and performance tests have been carried out on earth specimens with varying clay and additive content.

Firstly, development tests were carried out. According to the results, the earth-mix with 16% trass + 2% gypsum + 2,5% lime shows, whether they are dry or wet, to have the highest strength after 28 days of curing. Maximum compressive strength (8,6 MPa) was achieved with 16% water addition. Ettringite, which is a typical hydration product of Portland cement, was identified in all specimens. Precipitation of ettringite increases from 7 to 28 days of curing. Not the increase in gypsum content, but the increase in trass content contributes to the formation of ettringite. With higher trass content, ettringite steps forward with the strength of the mix-designs. Strength performance tests and XRD-analyses have proven that the mix-design containing only trass and lime but no gypsum, shows very weak strength. This means, gypsum as a source of sulphate plays a key role by the proposed stabilization approach.

Earth with trass+gypsum+lime (ETGL) shows 80% less shrinkage than that of plain earth. The average linear shrinkage value of tested stabilized earth specimens (SES) with 16% water is 0,36%, which is 3 times higher than that of normal strength concrete. Results have shown that the higher the gypsum content, the less the shrinkage. With high gypsum content the setting time is being dominated by the hydration of gypsum. The final setting of the specimens with high trass but less gypsum content is around 15h. On the contrary, plain earth paste was still soft after 48h. Results showed that 2% of citric acid can prolong the final setting up to ca. 25h. In addition, with the increase of gypsum content, the dry density of SES decreases. The higher gypsum content, the more porous the specimens.

Secondly, the performance tests were carried out. ETGL is 99,95% insoluble in water, where plain earth has lost 38,5% of its mass in 10 minutes. The results have shown that the higher trass content, the lower the capillary absorption. Moreover, expansions of about 0,005% were recorded after freeze-thaw cycles. Increasing gypsum and lime content caused increase in expansion. This behaviour may be attributed to delayed ettringite formation. The summary of properties of ETGL with 20% water addition is given in Table 39.

Table 39: Properties of ETGL

Bulk density (g/cm^3)	1,69-1,86
Flexural strength (MPa), 28d	0,15-0,30
Compressive strength (MPa), 28d	2,5-6
Shrinkage (%), 56d	0,39-0,65
Capillary water absorption	with increased trass content lower
Setting time (h)	0,28-14,75
Thermal conductivity	ca. 1,16

Discussions (Chapter 5):

The results have shown that the strength performance of earth with trass, gypsum, and lime (ETGL) is 4 times higher than plain earth. As cement stabilization praxis has shown, the cement addition for earth stabilization should be between 5-10%. An earth stabilized with 5-10% cement shows 4-8 MPa compressive strength (CS). However, with ETGL mixture 8,6 MPa CS can be achieved. In addition, the study of Lopez et al. (2011) is the most related one. They achieved 1,75 MPa CS with fly ash (pozzolan)+gypsum+lime combination, which is also remarkably lower than the results of ETGL. In addition, the CS achieved with TGL stabilization is significantly ahead of the results (1,7-4 MPa) of studies based on GL (gypsum+lime) stabilization. The significant advantage over relevant studies is that the improvement with TGL stabilization is achieved with only 4,5% $C0_2$ emitting additives (2% gypsum + 2,5% lime). This makes TGL stabilization 72% more environmentally friendly than the cement stabilization.

Shrinkage of ETLG is 80% less than plain earth but three times higher than that of normal strength concrete, which needs to be further improved. Where the final setting of ETGL with 8,6 MPa CS is ca. 15h., this is about 8-20 min by GL stabilizations and 3h - 10h by cement. This makes ETGL advantageous for transportation and casting. There is no comparable data for performance tests including water insertion, freeze-thaw-cycle or delayed ettringite test.

Conclusion and Outlook:

The method developed in this study allows for the stabilization of earth with the vernacular binder trass, gypsum, and lime (TGL). Earth stabilization by using TGL significantly improves the strength performance and durability of plain earth (PE). ETGL is water-insoluble and can withstand the freeze-thaw cycles. Thus, the two most critical drawbacks of PE, moderate strength, and low water stability, as mentioned in the introduction of the study, have been overcome. Another challenge of the proposed stabilization was reducing the environmental impact. With the TGL stabilization, a reduction in CO_2 emission of at least 72% could be achieved. The developed mixture is suitable for the production of stabilized earthen panels that are the first of its kind. Such a panel is practically feasible, reasonable, and could be integrated into earthen building standards in general and in particular DIN 18948, which is related to earthen boards and published in 2018. The dry ETGL mixture with improved strength and durability allows for the production of not only stabilized earthen panels but also further unfired earthen building materials. Finally, the results of this study will open a new avenue for earth stabilization and secure the implementation of this material in the conventional construction industry.

Zusammenfassung

Lehm wird seit der Antike als Baumaterial verwendet. Aufgrund einiger Nachteile wie geringe Wasserstabilität und mäßige Festigkeit wurde Lehm stabilisiert. Kalk, Puzzolan oder Gips waren die am häufigsten eingesetzten Zusatzstoffe zur Stabilisierung. In letzter Zeit ist Zement der am meisten verwendete Zusatzstoff geworden, da er die Festigkeit und Durabilität von Lehm verbessert. Die Herstellung von Zement verursacht jedoch hohe CO_2-Emissionen. Die Verwendung von Zement als Zusatzstoff verringert somit die ökologischen Vorteile des Lehms. Alternativen zur Zementstabilisierung sind derzeit weder wirksam genug, um die CO_2-Emission zu reduzieren, noch ermöglichen sie eine bessere Festigkeit und Durabilität als Zement. Daher befasst sich diese Arbeit mit der Wiederentdeckung eines vernakulären Ansatzes für die Lehmstabilisierungstechnik mit geringen Umweltauswirkungen, der darauf abzielt, Zement bei der Lehmstabilisierung zu ersetzen. Die Hauptforschungsfrage im Zusammenhang mit dem Forschungsziel ist:

Wie können vernakuläre Zusatzstoffe kombiniert werden, um eine umweltfreundliche und bauphysikalisch effiziente Stabilisierung zu ermöglichen, die es ermöglicht, Zement bei der Erdstabilisierung zu ersetzen?

Die folgenden Unterfragen können aus der Hauptfrage abgeleitet werden:

Kapitel 2: Welche Lehmarten eignen sich laut Baunormen für Lehmbauten und warum ist eine Lehmstabilisierung erforderlich?

Kapitel 3: Was sind die wichtigsten materiellen und forschungsrelevanten Merkmale der Methodik im Zusammenhang mit der vorgeschlagenen Stabilisierung?

Kapitel 4: Kann eine Kombination von Trass, Gips und Kalk als Zusatzstoffe als effizienter und umweltfreundlicher Weg zur Erdstabilisierung dienen?

Kapitel 5: Welche Verbesserungen werden gegenüber relevanten vergleichbaren Studien erzielt und welche Vorteile bietet die Verwendung dieser Mischung gegenüber herkömmlichen Alternativen?

Die folgenden Zusammenfassungen beschreiben die wichtigsten Ergebnisse für jedes der vier Kapitel.

Stand der Technik (Kapitel 2):

Der erste Schritt der Methode besteht in einer umfassenden Literaturrecherche zur Lehmstabilisierung (LS) insbesondere im Hinblick auf Baunormen und Bodenklassifizierung. Die wichtigsten Ergebnisse sind wie folgt:

Zement, Kalk, Flugasche (ein künstliches Puzzolan) und Gips sind übliche Zusatzstoffe, aber die Zementstabilisierung wird in der Literatur am häufigsten verwendet. Sie ist am weitestgehenden standardisiert, da sie die Festigkeit und Durabilität des Lehms erheblich verbessert. Es gibt keine einheitliche Klassifizierung, Prüfmethode oder Bestimmung der Art der Zusatzstoffe und ihrer Verwendungsbeschränkungen. In der Praxis werden hauptsächlich Zementprüfstandards verwendet. Zement zur LS ist jedoch aufgrund seiner hohen CO_2-Emissionen bei der Herstellung nachteilig. Dies ist die Hauptforschungslücke.

In den untersuchten Studien wurden hauptsächlich örtlich gewonnene und expansive Lehme verwendet was die Klassifizierung und Identifizierung des Lehmes erfordert. Dies ist die zweite Forschungslücke.

Laut den Ergebnissen der Literaturrecherche kann die Kombination aus Kalk, Puzzolan und Gips eine bedeutende Alternative sein, um Zement zur LS zu ersetzen. Es wurden jedoch nur wenige Studien mit künstlichem Puzzolan durchgeführt. Künstliches Puzzolan trägt indirekt zu CO_2-Emissionen bei und verbessert die Eigenschaften des Lehms nicht immer effizient. Dies ist die dritte Forschungslücke.

Darüber hinaus wurden in diesen Studien keine weiteren Experimente zur Bestimmung der bauphysikalischen Eigenschaften (performance tests) wie Wasserbeständigkeit, nasse Druckfestigkeit, Frost-Tau-Zyklen usw. durchgeführt.

Entwicklung des Mix-Designs (Kapitel 3):

In diesem Kapitel wird die Methodik zur Entwicklung des Mix-Designs einschließlich der experimentellen Materialien und ihrer Prozentsätze ausführlich beschrieben. Das Kernkonzept für die Entwicklung besteht darin, herkömmliche Zusatzstoffe zu kombinieren, um sowohl die Festigkeit und Haltbarkeit des Rohlehmes zu verbessern als auch die CO_2-Emissionen zu reduzieren. Der bei den Experimenten verwendete Lehm wurde unter Laborbedingungen hergestellt. Der Lehm besteht aus industriellem Ton und industriell standardisiertem Sand. Der industrielle Lehm ermöglichte es, die Notwendigkeit für Bodenaushub-, Klassifizierungs- sowie Bodeneignungstests zu eliminieren. Die in dieser Studie verwendeten Zusatzstoffe werden als herkömmliche, auf dem Markt erhältliche Zusatzstoffe klassifiziert.

28 Lehmmischungen mit unterschiedlichen Zusatzgehalten wurden hergestellt und verschiedene Tests durchgeführt, um die Leistungsfähigkeit dieser Technik zu untersuchen. Tabelle 1 zeigt die durchgeführten Tests.

Tabelle 1: Die in dieser Studie durchgeführte Tests.

Tests	
Kenngrößenprüfungen	bauphysikalische Kenngrößen
- Setzversuch	- Nasse Druckfestigkeit,
- Korngrößenverteilung	- Trockene Druckfestigkeit,
- Sedimentation	- Kapillarwasseranstieg,
- Schüttdichte	- Wassererosion,
- Porosität	- Wasseraufnahme,
- Nasse Druckfestigkeit	- Frost-Tau-Zyklus,
- Trockene Druckfestigkeit	- Trockenschwindmaß,
- Biegefestigkeit	- Verzögerte Ettringitbildung,
- Trockenschwindmaß	- VICAT-Abbindezeit,
- XRD Analyse	- Wärmeleitfähigkeit

Experimentelle Ergebnisse (Kapitel 4):

Die Prüfungen wurden an Lehmproben mit unterschiedlichem Ton- und Zusatzstoffgehalt durchgeführt.

Zunächst wurden die Kenngrößenprüfungen durchgeführt. Den Ergebnissen zufolge weist die Lehmmischung mit 16% Trass + 2% Gips + 2,5% Kalk nach 28 Tagen Aushärtung die höchste Festigkeit auf, unabhängig davon, ob sie trocken oder nass ist. Die maximale Druckfestigkeit von 8,6 MPa wurde durch 16% Wasserzugabe erreicht. Ettringit, ein typisches Hydratationsprodukt von Portlandzement, wurde in allen Proben identifiziert. Die Bildung von Ettringit steigt während der Aushärtungszeit von 7 bis 28 Tage deutlich an. Nicht die Zunahme des Gipsgehalts, sondern die Zunahme des Trassgehalts trägt zur Bildung von Ettringit bei. Bei höherem Trassgehalt bildet sich mehr Ettringit. Festigkeitstests und XRD-Analysen haben gezeigt, dass das Mix-Design, das nur Trass und Kalk, aber keinen Gips enthält, eine sehr schwache Festigkeit aufweist. Dies bedeutet, dass Gips als Sulfatquelle beim vorgeschlagenen Stabilisierungsansatz eine Schlüsselrolle spielt.

Lehm mit Trass+Gips+Kalk (ETGL) zeigt 80% weniger Schwinden als Rohlehm. Das durchschnittliche lineare Trockenschwindmaß von getesteten stabilisierten Lehmproben mit 16% Wasser beträgt 0,36% und ist damit dreimal höher als das von normalfestem Beton. Die

Ergebnisse haben gezeigt, dass das Schwinden umso geringer ist, je höher der Gipsgehalt ist. Durch den hohen Gipsgehalt wird die Abbindezeit von der Hydratation des Gipses dominiert. Die Endhärtung (final setting) der Proben mit hohem Trass, aber geringerem Gipsgehalt beträgt ca. 15 Stunden. Im Gegensatz dazu war Lehmpaste ohne Zusätze nach 48 Stunden noch weich. Die Ergebnisse zeigen, dass 2% Zitronensäure die Endhärtung bis zu 25 Stunden verzögern kann. Zusätzlich nimmt mit zunehmendem Gipsgehalt die Trockendichte von stabilisierten Lehmproben ab. Je höher der Gipsanteil, desto poröser die Proben.

Zweitens wurden die Tests zur Ermittlung der bauphysikalischen Eigenschaften durchgeführt. ETGL ist zu 99,95% in Wasser unlöslich. Im Vergleich dazu hatten die Rohlehmproben bei der Tauchprüfung innerhalb von 10 Minuten 38,5% der Masse verloren. Die Ergebnisse haben gezeigt, dass die Kapillarabsorption umso geringer ist, je höher der Trassgehalt ist. Darüber hinaus wurden nach Frost-Tau-Zyklen eine Expansion von etwa 0,005% verzeichnet. Zunehmender Gips- und Kalkgehalt führte zu einer Zunahme der Expansion. Dieses Verhalten kann auf eine verzögerte Ettringitbildung zurückgeführt werden. Die Zusammenfassung der Eigenschaften von ETGL mit 20% Wasserzugabe ist in Tabelle 2 angegeben.

Tabelle 2: Eigenschaften von ETGL mit 20% Wasserzugabe

Schüttdichte (g / cm³)	1,69-1,86
Biegefestigkeit (MPa), 28d	0,15-0,30
Druckfestigkeit (MPa), 28d	2,50-6,0
Trockenschwindmaß (%), 56d	0,39-0,65
Kapillare Wasseraufnahme	bei hohem Trassgehalt niedriger
Abbindezeit (h)	0,28-14,75
Wärmeleitfähigkeit	ca. 1,16

Diskussionen (Kapitel 5):

Die Ergebnisse haben gezeigt, dass die Festigkeit und Durabilität von Lehm mit Trass, Gips und Kalk (ETGL) viermal höher ist als die von Rohlehm. Wie die Literaturrecherche der Zementstabilisierung gezeigt hat, sollte der Zementzusatz zur Lehmstabilisierung zwischen 5 und 10% liegen. Ein mit 5-10% Zement stabilisierter Lehm zeigt eine Druckfestigkeit von 4-8 MPa. Mit der ETGL-Mischung kann jedoch eine Druckfestigkeit von 8,6 MPa erreicht werden. Die Studie von Lopez et al. (2011) ist für die Einordnung der Ergebnisse am relevantesten. In dieser Studie wurde eine Druckfestigkeit von 1,75 MPa mit der Kombination Flugasche (Puzzolan) + Gips + Kalk erreicht, was deutlich niedriger ist als die Ergebnisse von ETGL. Darüber hinaus liegt die mit der TGL-Stabilisierung erzielte Druckfestigkeit deutlich über den Ergebnissen von 1,7-4 MPa von Studien, die auf der Stabilisierung von Gips + Kalk basieren. Der wesentliche Vorteil gegenüber den vorherigen Studien besteht darin, dass die TGL-

Stabilisierung mit 2% Gips und 2,5% Kalk nur 1,9 kg CO_2 verursacht und das 71,3% weniger ist als zementstabilisierter Lehm mit gleicher Druckfestigkeit.

Das Schwinden von ETLG ist 80% geringer als das von Rohlehm, jedoch dreimal höher als das Schwinden von normalfestem Beton und sollte daher weiter verbessert werden. Die Endhärtung von ETGL mit 8,6 MPa Druckfestigkeit wird nach ca. 15 Stunden erreicht. Im Vergleich dazu ist diese bei Gips+Kalkstabilisierungen nach ca. 8-20 Minuten und bei Zement nach 3-10 Stunden erreicht. Dies macht ETGL für Transport und Gießen vorteilhaft. Es gibt keine vergleichbaren Testdaten für bauphysikalische Eigenschaften, einschließlich Tauchprüfung, Frost-Tau-Zyklus oder verzögertem Ettringit-Test.

Fazit und Ausblick:

Die in dieser Studie entwickelte Methode ermöglicht die Stabilisierung des Lehms mit den vernakulären Bindemitteln Trass, Gips und Kalk (TGL). Die Lehmstabilisierung durch Verwendung von TGL verbessert die Festigkeit und Durabilität von rohem Lehm erheblich. ETGL ist wasserunlöslich und kann den Frost-Tau-Zyklen standhalten. Somit wurden die beiden kritischsten Nachteile von rohem Lehm, geringe Festigkeit und geringe Wasserstabilität überwunden. Darüber hinaus konnte mit der TGL-Stabilisierung eine Reduzierung der CO_2-Emissionen um mindestens 72% erreicht werden. Die entwickelte Mischung eignet sich als erste ihrer Art zur Herstellung von stabilisierten Lehmbauplatten. Ein solches Paneel ist nun praktisch umsetzbar und könnte in Lehmbaunormen im Allgemeinen und im Besonderen in die DIN 18948 integriert werden, die sich auf Lehmbauplatten bezieht und 2018 veröffentlicht wurde. Die trockene ETGL-Mischung mit verbesserter Festigkeit und Durabilität ermöglicht nicht nur die Herstellung von stabilisierten Paneelen, sondern auch weiteren ungebrannten Baumaterialien. Schließlich werden die Ergebnisse dieser Studie einen neuen Weg zur Lehmstabilisierung eröffnen und die Implementierung dieses Materials in der konventionellen Bauindustrie ermöglichen.

Appendix

A. Earth material

The standardized sand is composed of various grain sizes as can be seen in Figure 91. To prepare the earth needed for experimental tests, the standard sand and industrial clay were homogenously mixed.

Figure 92: a: industrial clay and standard sand sieved with various sieves, b: standard sand and clay before mixing.

Figure 93: a- Earth mixture with additives and 20% water, b- a series of cast specimens

B. Steel moulds

The steel moulds used for preparation of various stabilized specimens can be seen in Figure 93. The steel mould allowed an accurate moulding.

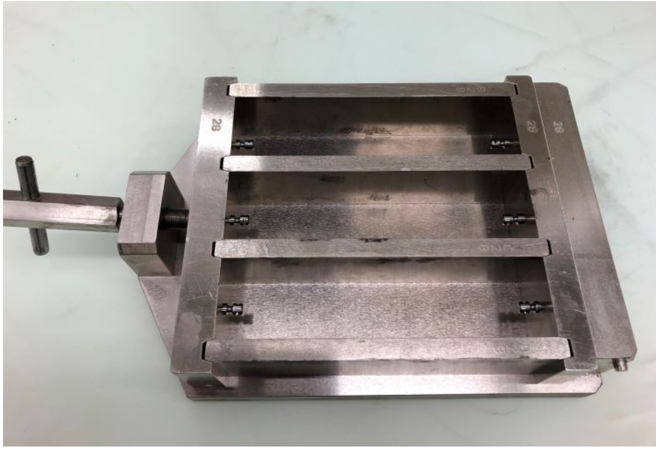

Figure 94: Steel mould used for casting the specimens for experimental tests

C. Strength performance test, equipment, and tested specimens

The Figure 94 shows the apparatus used for both flexural strength and compressive strength.

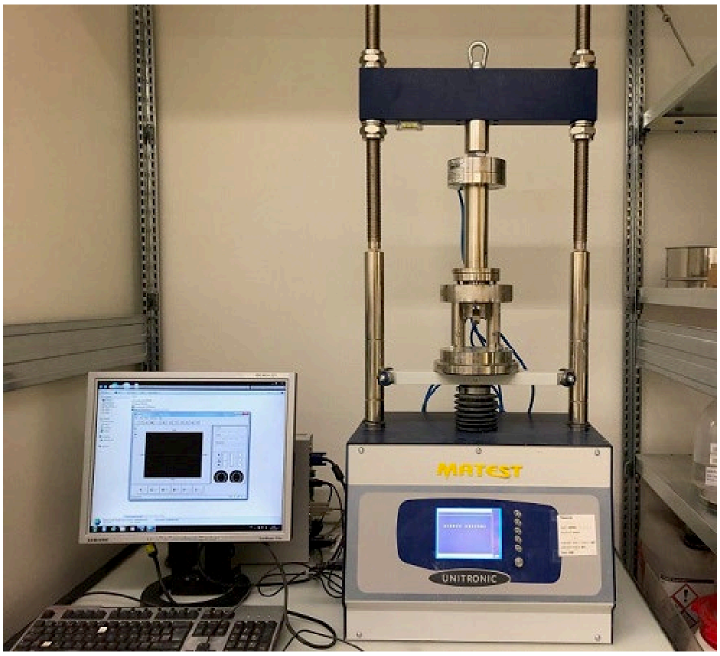

Figure 95: Strength performance testing device Walter + Bai 502/4000/100

The specimens after compressive strength test are shown in Figure 95. As can be seen from the figures both SSS and SES show similar failure modus.

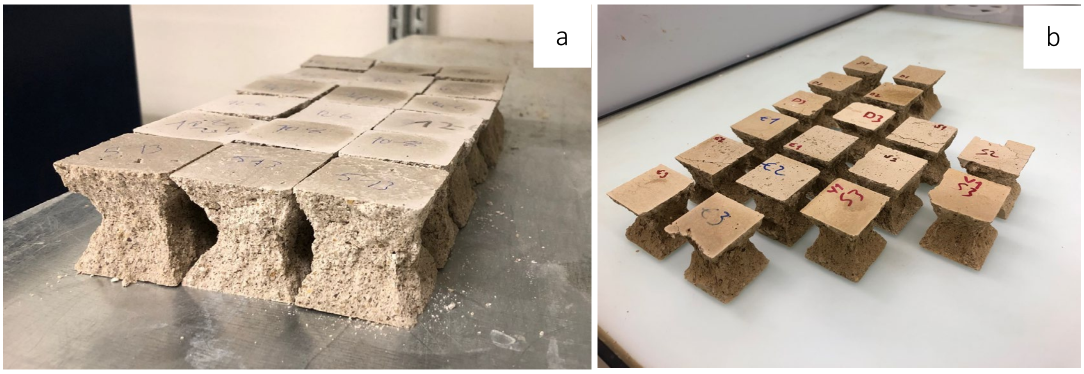

Figure 96: a: pressed SSS, b: pressed SES

The SES placed into the water tank for wet compressive strength experiment are shown in Figure 96. The compression test has been conducted after 24h of saturation.

Figure 97: SES in water tank after 24 hours

D. X-Ray diffraction analyses specimens and XR-diffractometer

Figure 97 shows the XR-diffractometer of ClayLab at ETH-Zürich used for determination of mineralogical composition of various mixture.

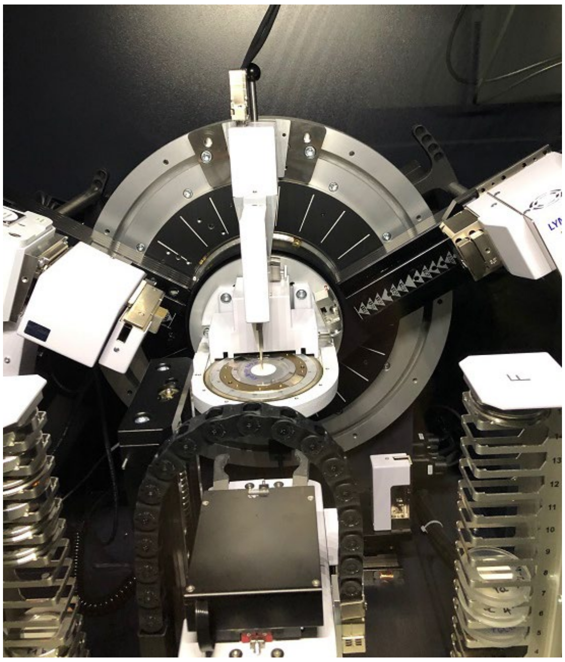

Figure 98: XRD- diffractometer with installed mould specimen.

The preparation process of a mould specimen can be seen in Figure 98. After mixing additives and water together the specimens were left for curing. The specimens were then used to prepare a solution for which ethyl alcohol was used. Using ethyl alcohol accelerates the drying process of the solutions. The solution was sieved to ensure homogeneity. The solutions were then left out for drying. Finally, the dried residues were used to prepare the mould specimens, which were placed in XR-diffractometer for the measurement.

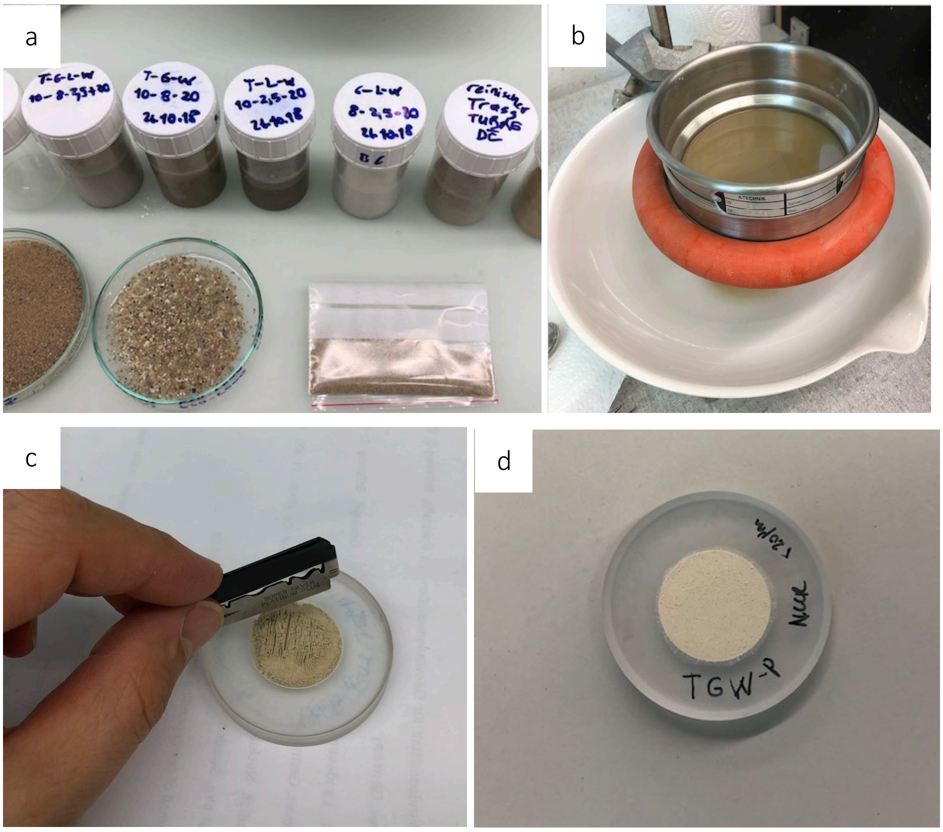

Figure 99: a: fluid specimens for XRD analyses left over for curing, b: sieving the grounded samples for drying, c: preparation of mould specimens for test, d: a ready mould specimen for XRD analyses.

E. Shrinkage apparatus

Figure 99 shows the shrinkage apparatus used for shrinkage measurements of SES, expansions of specimens used the analyse the effect of DEF and FTC.

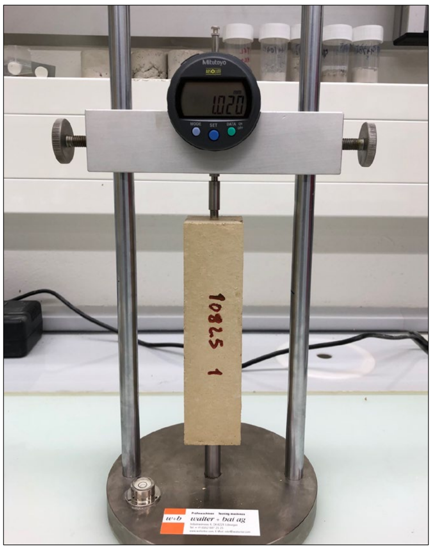

Figure 100: Mitutoyo ABSOLUTE Digimatic 12,7 mm 543-400B Serie 543 used for shrinkage measurements.

F. Setting time apparatus

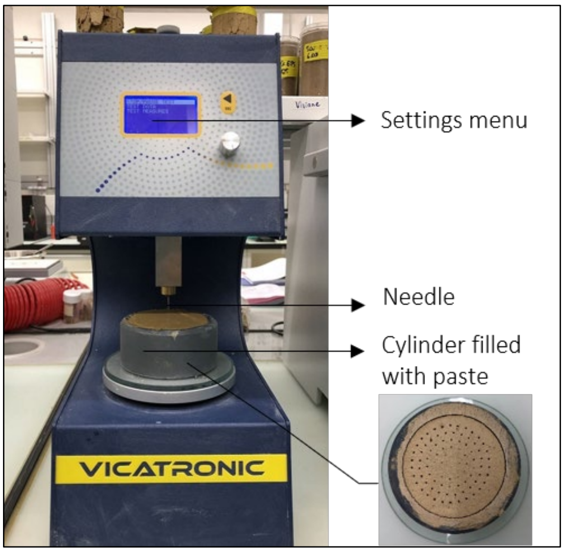

Figure 101: Vicatronic Automatic Vicat Recording Apparatus with installed specimen ready for testing

G. Bulk density apparatus

Figure 102: Micromeritics GeoPyc 1360 DryFlo-Pycnometer with installed mould

H. Porosity measurement apparatus

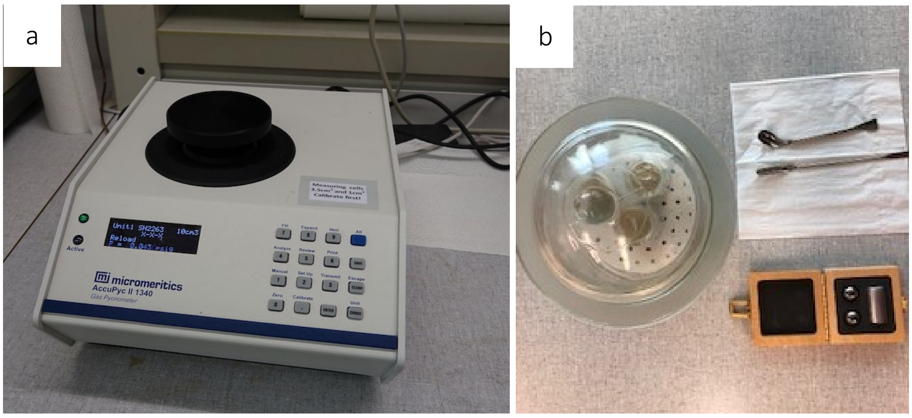

Figure 103: a: Micromeritics AccuPyc 1330 He-Pycnometer, b: calibration devices and dried specimens.

I. Water insertion equipment and experiment setting

Figure 104: Experimental setting for determination of loss of mass in contact with water

J. Capillary absorption experiment setting

Figure 104 shows the experimental setting for determination of capillary water absorption and capillary water rise. The SES were marked with 1mm lines from bottom to the top of the specimen and the water rise was observed as described in the methodology.

Figure 105: Experimental setting for determination of capillary water absorption and water rise.

The standard test specimen according to ASTM C1585, is a 100 ± 6 mm diameter disc, with a length of 50 ± 3 mm. However, in this study, 160x40x40mm specimen bars were used. The side surfaces and the top surface of the specimen bars were sealed with a transparent wax.

K. Freeze-thaw cycle specimens and climate chamber

The climate chamber used for the FTC test and the specimens placed into the climate chamber are shown in Figure 105. The tempering protocol is given in Figure 106.

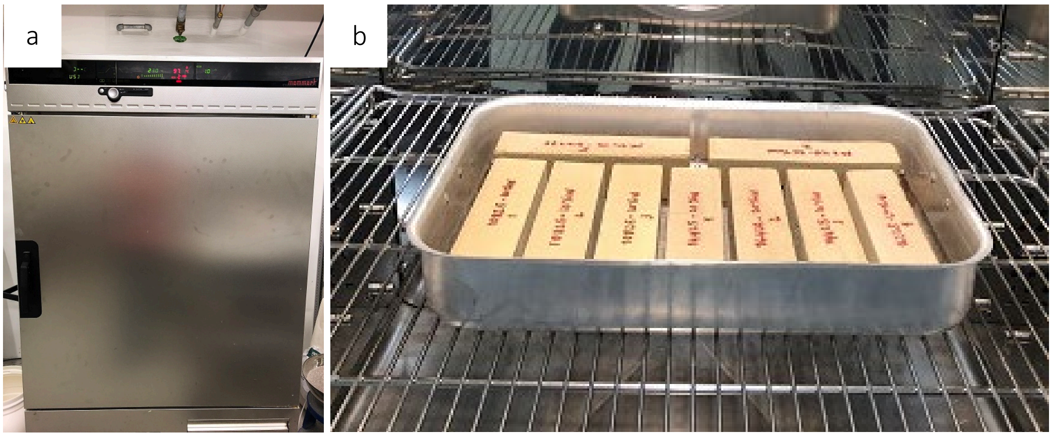

Figure 106: a: climate chamber, b: specimens placed in climate chamber to determine the effect of FTC

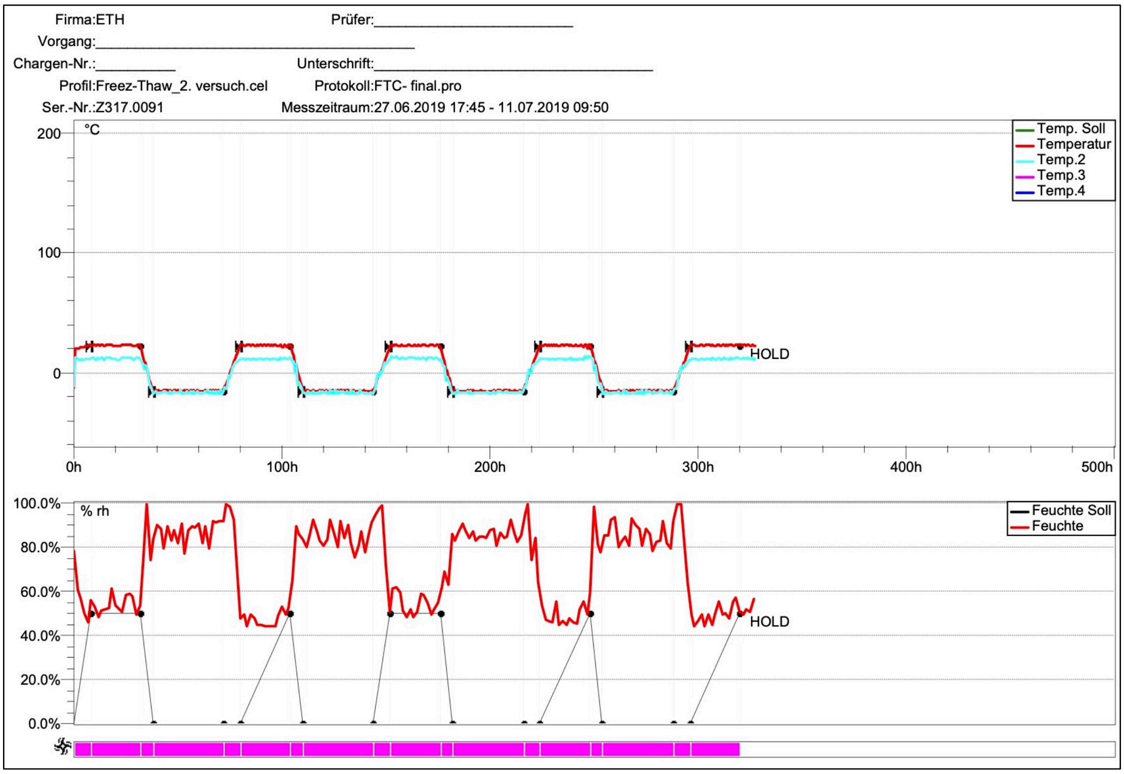

Figure 107: Tempering protocol for DEF.

L. Delayed ettringite experiment setting

The test protocol of DEF test adapted from Fu method is given Table 40.

Table 40: Delayed Ettringite test protocol

DELAYED ETTRINGITE TEST PROTOCOL	
Methods	
Fu	(The method used in this study)
Duggan	has been progressively abandoned, as it does not represent practical heating regime and heating program is very severe.
Mix design	1082,5 (TGL) 865 (TGL) 1622,5 TGL)
Size	40x40x160mm. (Fu Method 25x25x160mm)
Samples	9 pieces
Procedure	
1	prepare the specimens with 3 different mix design
2!	dry them at room temperature (23°C), at relative humidity for 24h (in this study the specimens were left over for 48h)
3	measure the length of the specimens (first measurement)
4	put the specimens in their mould into the moist curing room for 1h
5	Put samples with moulds in to the plastic container, cover it tightly, seal it
6	Put container in the oven.
7	Raise the temperature to the designated temperature 95°C in 1 h
8	Maintain the temperature at 95°C for 12h
9	turn off oven and let it for cooling for 4 h
10	Remove the specimens from the moulds
11	be sure that they are properly identified
12!	place the specimens in water tank maintained at 23°C for 6 hours (in this study suction method was used to make the specimens wet)
13	make the initial length measurement (zero-day measurement)
14	dry the specimens in the oven at 85°C for 24h
15	cool the specimens to the room temperature
16!	Store the specimens into the saturated lime water at 23°C (in this study suction method was used to make the specimens wet)
17	repeating measurements every 7 days

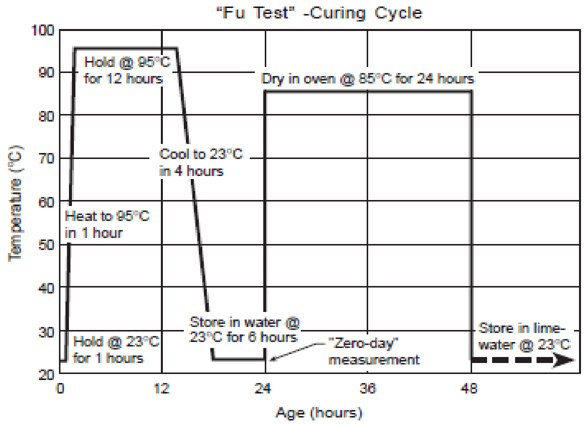

Figure 11 - Fu Method to Assess DEF
(Thomas, Personal Communication, 2000 after Fu 1996)

Curing Cycle	
Time (hour)	
24	initial drying
1	moist curing room
1	first raising temperature up to 95°C
12	maintaining the temperature at 95°C
4	cooling
6	storing water tank 23°C
24	drying in oven at 85°C
1	cooling to 23°C
	Storing into the lime water tank and repeating the length measurement every 7 days
Expansion limit: 0,04% (according to ASTM specification for Portland cement)	

Figure 107 shows the experimental setting. SES were placed into the water tank filled with SLW. The expansion and weight change were recorded as described in the test methodology.

Figure 108: Experimental setting for delayed ettringite formation.

M. Thermal conductivity

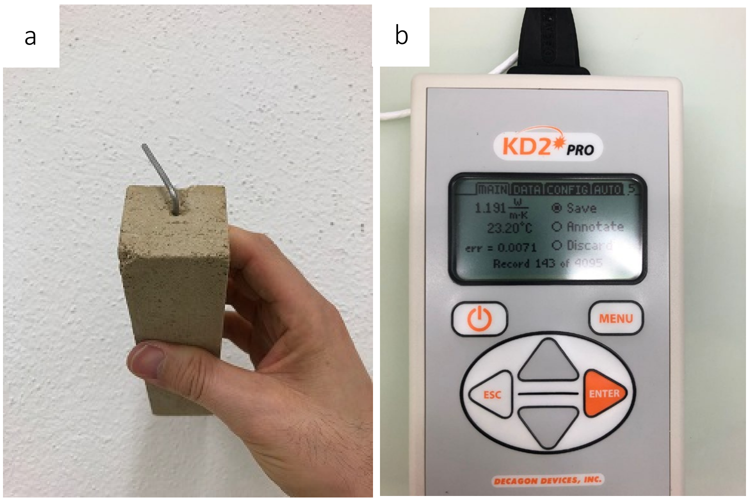

Figure 109: a: SES ready for measurement, b: KD2 Pro apparatus

N. Slump test

The technical drawing of the steel slump mould, used for the slump test, is shown in Figure 109.

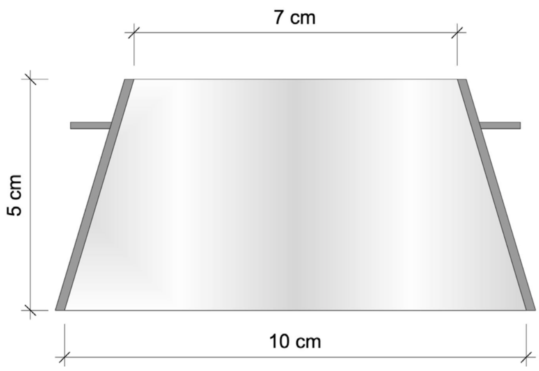

Figure 110: Slump mould used for slump test.

Ehrenwörtliche Erklärung

Ich erkläre hiermit ehrenwörtlich, dass ich die vorliegende Arbeit ohne unzulässige Hilfe Dritter und ohne Benutzung anderer als der angegebenen Hilfsmittel angefertigt habe. Die aus anderen Quellen direkt oder indirekt übernommenen Daten und Konzepte sind unter Angabe der Quelle unmissverständlich gekennzeichnet.

Bei der Auswahl und Auswertung folgenden Materials haben mir die nachstehend aufgeführten Personen in der jeweils beschriebenen Weise unentgeltlich geholfen:

1. Dr. Michael Plötze von der ETH-Zürich; Ausführung und Bewertung der XRD Analyse.

2. Natalia Pires Martins von der ETH-Zürich; Bewertung der XRD Analysis

Weitere Personen waren an der inhaltlich-materiellen Erstellung der vorliegenden Arbeit nicht beteiligt. Insbesondere habe ich hierfür nicht die entgeltliche Hilfe von Vermittlungs- bzw. Beratungsdiensten (Promotionsberater oder anderen Personen) in Anspruch genommen. Niemand hat von mir unmittelbar oder mittelbar geldwerte Leistungen für Arbeiten erhalten, die im Zusammenhang mit dem Inhalt der vorgelegten Dissertation stehen.

Die Arbeit wurde bisher weder im In- noch im Ausland in gleicher oder ähnlicher Form einer anderen Prüfungsbehörde vorgelegt.

Ich versichere ehrenwörtlich, dass ich nach bestem Wissen die reine Wahrheit gesagt und nichts verschwiegen habe.

Coburg, 21.06.2021

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