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„Ohne Spekulation gibt es keine neue Beobachtung“

Charles Darwin

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1. Introduction

This study aimed to explore and develop clay formulations suitable for 3D printing as a construction material. Due to its inherent properties, clay offers promising possibilities for various construction applications. The investigation focused on mixtures of two types of clay (BL and BLF) and two types of sand (Quartz and S-sand). The main objectives were to analyze the drying characteristics, shrinkage, warping behavior, and dimensional stability of these formulations upon drying.

Additionally, the study assessed the mechanical properties of the resulting components and the potential for using these optimized formulations in ejection and casting methods. The materials used in construction are commonly known as building materials. In today's world, we notice a growing necessity to employ a combination of building materials to accomplish the needed attributes because a single material, in terms of economics, efficiency, and performance, usually cannot fulfill the set of properties required.

1.1 Construction Materials

Structures are constructed using a variety of naturally occurring elements, such as clay, sand, wood, stone, and even a little vegetation. In addition to natural resources, several man-made materials are utilized in conjunction with natural materials. The building industry utilizes a broad range of clay and a few of them are non-renewable. However, in the light of changing environmental conditions, it is becoming increasingly vital to examine buildings' much-discussed ecological impact. A fresh interest has emerged in earthen construction materials. These materials, such as adobe, rammed earth, or cob, have gained renewed interest due to their ecological benefits. They are often sustainable and environmentally friendly alternatives to conventional building materials like concrete and steel. Their thermal properties can also contribute to energy efficiency in buildings. This resurgence in interest has led to exploring new applications and products using these materials, promoting their use in modern construction practices focused on sustainability and ecological impact. A substantial number of people around the world reside in homes constructed primarily or entirely from clay and compressed earth. There are as many as 40 distinct clay construction methods in use, but this study specifically examined two different methods for rammed earth construction. Additionally, the construction industry has adopted digital techniques for working with clay-based materials. [1,2]

It is fair to state that concrete and steel are currently the two building materials most often utilized in construction [2]. More than 30 and up to 50% of all resources used in Europe are used for building. Among them are primarily timber, stone, clay, sand, gravel, limestone, metal, copper and approximately 42% of the overall weight of the components is made up of concrete. Concrete is produced using unsustainable methods, in contrast to wood, and it cannot be rebuilt after being broken down for building. Steel must be melted at high temperatures each time it is recycled in order to be transformed into a new material, and this process requires large amounts of energy, which commonly originates from fossil resources. The environment is thus still put at risk by recycling steel for industrial production, which emits greenhouse gases (GHG) because it takes energy to run the steel factories, and the majority of the power and heat still comes from burning fossil fuels. Similar quantities of energy are needed to create concrete, but the chemical process of creating cement requires a certain amount of carbon dioxide. For every metric ton of cement produced, approximately 1,370 kg of CO2 are emitted. Furthermore, the production of steel and cement, which are the primary components of concrete, accounts for 10% of global greenhouse gas emissions. Alternatively, using clay in construction can have positive environmental and greenhouse gas effects, as it has a low energy content due to its natural availability. This results in less energy consumption and fewer GHG emissions associated with building materials, making clay a sustainable and eco-friendly option for construction. Since primary crushing and delivery use the majority of the energy in clay-based materials, local production of clay soil reduces the primary energy requirements to close to zero. However, stabilizing additives used in earth bricks as well as the activities involved in transporting them to the construction site have a significant impact on GHG emissions. Unfixed earth bricks emit just 95 kg CO2 eq/m3 compared to fired clay bricks, for which roughly 560 kg CO2 eq/m3 are emitted. These numbers demonstrate the massive impact clay-based products could have, particularly when burned clay bricks are replaced. [2,3]

The significance of clay becomes apparent when considering that construction accounts for 40% of overall energy use, while the construction sector utilizes 30% of our resources and is responsible for generating 40% of our annual waste [3]. Recent studies [4] indicate that standard clay can serve a role as effectively as more specialized materials, offering a sustainable building option that has the potential to reduce greenhouse gas emissions and enhance building energy efficiency. Clay possesses several advantages when compared to other construction materials. Particularly noteworthy is that some alternatives are costly, complex to create, toxic, or environmentally unfriendly. Clay naturally forms as a result of the weathering of rocks, making it universally accessible and locally applicable in construction.

It encompasses a spectrum of particle sizes, from gravel and sand to silt and clay. Its plasticity allows for reshaping with the introduction of water, making it a highly recyclable construction material. As Martin Rauch emphasizes, "Clay is the only construction material that can be reused eternally without diminishing quality." [5,7].

2. Clay

Clay is a type of fine-grained natural soil material that contains clay minerals with the basic formula X Al_2O_2·Y SiO_2·Z H_2O. Clay materials can be composed of solid, liquid, and vapor phases. The solid phases that involve shaping the structural components of clay materials are composed of mineral and organic phases. The mineralogy can be roughly separated into clay and non-clay minerals, including weakly crystalline inorganic phases known as "amorphous" phases. Minerals are crystalline solids with well-ordered crystal structures by definition; however, clay minerals and other inorganic phases in clay materials are usually less crystalline than minerals such as quartz and feldspar. The word "clay" is applied to represent a variety of substances with particle sizes of smaller than two micrometers as well as the group of minerals listed in the next section that have similar chemical compositions and crystal structure traits. As a result, clays can include a combination of finer-grained clay minerals and crystals the size of clay from other minerals, including quartz, carbonate, and metal oxides. The majority of clays and clay minerals may be found on or near the earth's surface. They are generated by the weathering of solid or loose rock or by the unsorted deposition of their constituents. [7,9]

"Loam" is a combination of clay, sand, and silt that benefits from the characteristics of these three diverse textures, favoring drainage, airflow, and fertility. These soils are simple to deal with and have excellent drainage because they can be either sandy or clay loam, depending on the prevailing composition. Mountain loam, bedrock loam, boulder loam (glacier), loess loam (loess), and floodplain loam are classified based on how they were produced. 'Fat' clay (> 30% clay) and 'lean' clay (15% clay) are terms used to describe the percentage of clay in the soil. Utilizing loam in construction saves time and money by avoiding extensive transportation routes and should ideally be obtained straight from the excavation pit and treated on the spot, reducing the cost of transporting any additions (sand, gravel, etc.). [10]

Clay can be dug out of the ground and applied as a construction material right away. To be able to use the local clay directly, the clay's quality must first be assessed, as well as its compatibility with the specific clay construction technique. Mineral or vegetable additions can help with compressive, tensile, and abrasion resistance, as well as crack prevention and moisture absorption. Small quantities of clay can be added to construction materials to boost their thermal insulation capability. Also, clay is available in two forms: dry clay and powdered clay. Clay flour is crushed clay that has been dried and can be used to improve the binding strength of lean building soil. [11,12]

2.1 Types of clay

As shown in Figure 1, there are six main types of soil: loam, sand, silt, peaty, chalky, and clay, with the primary difference being the size of their particles. 'Fat' clay > 30% and 'lean' clay 15% clay is a term used to describe the percentage of clay in the soil. They can be used in a variety of applications because of their diverse chemical and physical characteristics. Although clay is a form of soil, the main distinction between soil and clay is that clay has the property of flexibility upon wetness, while soil is a substance that contains organic matter, minerals, liquids, and organisms. Silt, clay, and soil are natural construction materials that can be found in a variety of compositions under the top layer all over the earth. Sand and clay are equally important for building, as is the type of clay. Silt is created when other natural rock is broken down and is composed of clay and sand. Each and every piece of silt is unique. Silt soils are found in a variety of colors, from white to light beige, yellow to ochre, brown to gray blue, and red. Depending on its composition, silt is a more or less ductile material in its damp form that becomes load-bearing after being allowed to air dry. [12,13]

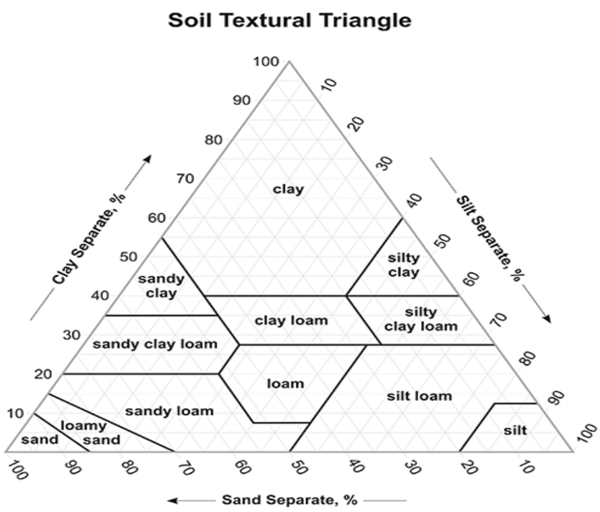


Figure 1: soil classification systems: the texture triangle of the [USDA 1951, 2017].

Cob is a clay-based construction material that is gaining popularity due to its simplicity and versatility. It is composed of clay, water, fibrous organic material, and often lime. The composition of clay can vary, and if the balance is not ideal, it can be adjusted by adding sand or clay. Cob construction is prevalent in various regions of Africa and Asia and is particularly useful for repairing old buildings in Europe. It offers a load-bearing design option but is limited in terms of height due to its relatively poor compressive strength. In mild climatic zones, it is crucial to consider appropriate combinations of thermal insulation materials. Reed mats, for instance, can help maintain the diffusion permeability of clay walls. Moreover, prefabricated load-bearing rammed earth elements with or without integrated core insulation are now available, expanding the possibilities of cob construction. [13].

Adobe is one of the oldest known building materials and also utilizes clay as its primary component. It involves making bricks by molding a clay and straw mixture and allowing it to dry in the sun. These bricks are then used to construct walls by stacking them in layers and bonding them with a mortar made of the same mixture. Adobe walls are known for their thermal mass, which helps regulate indoor temperatures in areas with significant day-to-night temperature variations. To enhance the durability of adobe walls, surface treatments such as plaster, bitumen, or linseed oil are often applied. Stabilizers like bitumen and Portland cement can be introduced to improve the soil's resilience and resistance to weather. [14]

Clay-based construction materials, including rammed earth, cob, and adobe walls, offer sustainable alternatives to traditional construction methods. These techniques utilize locally available resources, provide excellent thermal mass properties, and can be used for load-bearing designs. However, it is crucial to consider their limitations, such as height restrictions and compressive strength, when planning construction projects. With careful implementation and the integration of modern technologies, these clay-based materials have the potential to contribute to environmentally conscious and resilient building practices. [14,15]

2.1.1. Rammed earth

Rammed earth as a building material is composed of a combination of clay, rock particles, and water. This unique combination results in a material that lacks a defined crystalline structure, making it amorphous in nature. Clay can be used to create either bricks or rammed earth. Rammed earth is characterized as a damp and crumbly substance that, upon drying, achieves a bulk density ranging from 1700 to 2200 kg/m^3. Due to its density, rammed earth is suitable for construction, particularly for load-bearing components. However, when employed for exterior walls, clay bricks are known to be susceptible to moisture and require protection, such as a canopy. A decent soil mix for rammed earth should be composed of 60–70% sands, gravels, and fines and 30–40% clays. Soil types used include sandy clays, gravelly clays, and clayey sands. The cohesiveness of the earth and the grading curve (grain size distribution) of the rock grains, as well as any other additions such as fibers, both affect how strong the rammed earth is. Generalizations in the specialized literature suggest that the grading curve should be broad and flat. To produce the greatest strength, the aggregates should be "packed" as tightly as possible. Compressive strength tests should be performed on rammed earth structures. As a general rule, the typical compressive strength should not be less than 1.5 N/mm^2 or 2.0 N/mm^2 for walls between 3.0 and 6.0 m in height. [15,16].

2.2 Formation of clay and clay minerals

There are many different habitats where rock is formed, such as soil horizons, continental and marine sediments, geothermal regions, volcanic deposits, and weathering rock formations. Most clay minerals are created when rocks come into contact with moisture from air, water, or steam. These circumstances include, for example, weathering boulders on a slope, sediments on the bottoms of lakes or oceans, deeply buried sediments holding pore water, and rocks in contact with water that has been heated by magma (molten rock). It is possible for clay minerals to develop from preexisting minerals in any of these conditions and could be conceivable for relatively pure clay deposits to be created through extensive modification of rocks to clay minerals. [16]

Important steps in the process that creates sedimentary rocks include the movement and deposition of clays and clay minerals created by the erosion of older continental and marine rocks and soils. Approximately 70% of the old sedimentary rock record is made up of mud stones, which include 50% clay-sized pieces and sales, which are coarser than mud stones but may also contain clay-sized particles Currently, 40% of deep ocean basins and 60% of marine continental shelves are covered by sedimentary settings that include mud. Continental aquatic habitats, including lakes, rivers, estuaries, and deltas, also include significant amounts of fine-grained sediments. It is obvious that clays and clay minerals are important elements of both ancient and contemporary sedimentary ecosystems. [17,18]

Common silicate substances, including quartz, feldspar, and volcanic glasses, together with carbonates, non-crystalline iron oxides, and primary clay minerals, are changed into more stable clay minerals during diagenesis, mostly through dissolution and recrystallization. Other forms of rock may also act as supplies for bentonite beds, which often develop from altered volcanic ash. Fuller's earth is a type of clay mineral deposit that has a high capacity to absorb water. For instance, both bentonite and fuller's earth have absorbent qualities that make them for a variety of applications, including drilling mud, foundry sand bond, binding agents for pelletizing iron ore and bleaching liquids, absorbents for oil, grease, animal waste and carriers for pesticides and fertilizers. Bentonite is also utilized in paper production when combined with polyacrylamide and as a soil liner for environmental containment purposes. [18]

Clay minerals also include kaolinite and montmorillonite. The main distinction between kaolinite and montmorillonite is that each repetitive unit of kaolinite includes one silica tetrahedral sheet and one aluminum octahedral sheet, whereas each repeating unit of montmorillonite contains two silica tetrahedral sheets and one aluminum octahedral sheet. Additionally, while montmorillonite is typically white, light pink, or scarlet in color, kaolinite is typically white to cream. Due to its beneficial properties, montmorillonite is suitable for a wide range of uses, including being used by the oil drilling industry as a drilling mud component, a soil additive, a manufacturing sand component, a method of desiccation to remove moisture from air and gases, a catalyst, and various medical and pharmacological applications. Researchers were able to determine that clays are made up of a few groups of crystalline minerals, thanks to the development of X-ray diffraction methods in the 1920s and the subsequent refinement of microscopic and thermal processes. The development of electron microscopic techniques was very helpful in identifying the distinctive size and form of clay particles, too. [19,20]

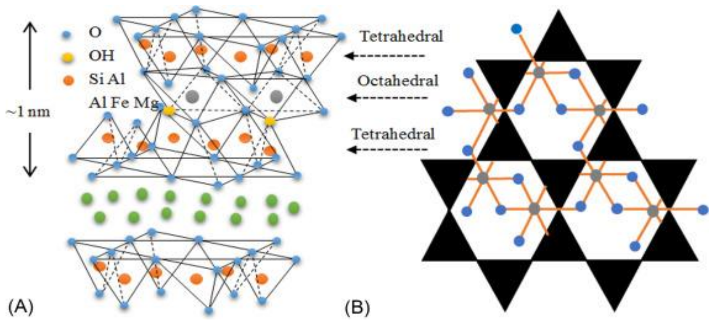


Figure 2: Layer clay minerals. The side view illustrates the two layers of silicon tetrahedron (A) sandwiching the aluminum octahedron (B). [20]

2.2.1 Erosion

Erosion is the gradual wearing away and removal of soil or other materials from the earth's surface. When it comes to clay as a building material, erosion can have implications for its stability and durability. Clay soil, due to its fine particles, is susceptible to erosion by water. This can lead to problems such as foundation instability, land slippage, and drainage issues for buildings constructed with clay. To mitigate these issues, proper site preparation, erosion control measures, and surface water management techniques should be employed to minimize erosion and ensure the longevity of clay structures. Overall, erosion is a natural process that alters the Earth's surface and managing it is crucial for preserving soil fertility, protecting ecosystems, and mitigating environmental impacts. [21]

2.2.2 Diagenesis

Diagenesis is the process that transforms sediments into sedimentary rock through physical, chemical, and biological processes occurring after initial deposition. This includes compaction, where sediments are squeezed by the weight of overlying materials, and cementation, where minerals precipitate and bind sediment grains. Recrystallization restructures original minerals into new crystal forms without melting, while chemical alterations form new minerals and change existing ones through reactions. Diagenesis typically occurs at low to moderate temperatures and pressures, characteristic of shallow burial environments.

Surface weathering produces clay minerals, which, through diagenesis, transform into durable materials suitable for construction. These clays are essential in creating sedimentary rocks and are commonly used in making bricks, tiles, and other building components. The diagenetic processes enhance the strength and longevity of these materials by improving their resistance to water and environmental factors. [22,23]

2.2.3 Weathering

The process of weathering is a natural phenomenon that causes materials to break down over time due to exposure to the elements, leading to cracks and structural damage . In clay construction, weathering can have a negative impact on the stability and durability of buildings and structures. To mitigate the effects of weathering on clay construction, builders and engineers need to properly assess site conditions and use appropriate construction techniques such as adding reinforcing materials, applying protective coatings or sealants, and ensuring proper drainage and ventilation. Failure to do so can result in structural damage, reduced longevity of the building, and increased maintenance costs over time. On the other hand clays and clay minerals now occur at the Earth's surface, mostly as a result of the weathering of rocks and soil. The weathering process comprises both physical and chemical disintegration, which transforms original minerals into clay minerals. Weathering is uneven, and the same clay sample can go through several phases of breakdown. The original kind of rock, the water-to-rock ratio, the temperature, the presence of organisms and organic material, and the duration are all factors that affect rock weathering and soil formation. The varieties of clay minerals present in weathering rocks heavily influence how the weathered rock responds to varied environmental circumstances, for instance, humid-tropical, dry-tropical, and temperate conditions. Since clay is a byproduct of weathering and may thus be found virtually anywhere on the earth's surface, it is quite widespread across the planet. In Austria, the Lower Austrian area is notable because it boasts the country's greatest clay reserves. However, there are also clay deposits in Vorarlberg, specifically the flysch rock, which is composed of clay and rock grains of various sizes. Therefore, flysch rock is ideal for making rammed earth. [23,24]

2.3 Physical and chemical properties of clay and clay minerals

The traits common to all clay minerals arise from their layered structure, chemical composition, and size. These minerals consist primarily of silica, alumina, magnesium, and water. Within their foundational crystalline units, two distinct categories emerge based on the arrangement of these ions. The silicon-oxygen tetrahedron comprises silicon surrounded by four oxygen atoms, forming a silica sheet. By contrast, aluminum or magnesium octahedra consist of six hydroxyl units encircling aluminum, creating gibbsite (when aluminum dominates) or brucite (when magnesium dominates) sheets. These sheets collectively constitute the atomic structure of clay minerals, comprising two fundamental components: the octahedral sheet and the tetrahedral sheet. In the octahedral sheet, oxygen and hydroxyl atoms densely pack around aluminum, iron, or magnesium atoms arranged in octahedral coordination. The silica tetrahedral layer involves a silicon atom positioned at an equidistant point from four oxygen atoms or hydroxyl groups, forming a central tetrahedral configuration. Figure 3 shows that the atomic structure of clay minerals is comprised of two fundamental components: the octahedral sheet and the tetrahedral sheet. [25,26]

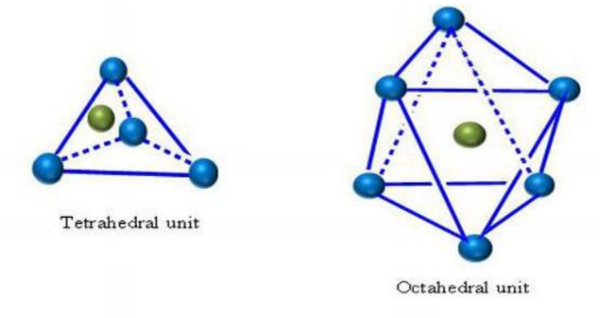


Figure 3: Unit's tetrahedral and octahedral structure of clay minerals. [27]

All clay minerals have a strong attraction to water and some types of clay, when wet, can double in thickness and swell easily. Although only approximately half of the total water they can keep is accessible to plants, they can still hold more than most other soil types and crops seldom experience drought because of this. A slurry is created when an amount of clay is inserted into water and clay equally disperses itself throughout the liquid. The majority of clays have the capacity to absorb ions from a solution and release them when the environment changes. Clay soils are incredibly sticky and roll like plasticine when they are wet. Loam is not as plastic as clay and also not as impermeable to water since the proportion of smaller particles (clay minerals) is much larger in clay. The amount of water in the formulations affects shrinkage. Clay swells when water is added and shrinks when it dries, which is particularly important in clay building. Rich loams shrink more quickly than other soil types, but this can be mitigated by adding sand to the mixture. Also, the reversible nature of the swelling process in some clay minerals means that when these minerals absorb water they swell but they return to their original size when the water evaporates or is removed. This property can be useful in various applications, such as in the creation of clay sculptures or in controlling the swelling behavior of soils. Hydration and dehydration can vary the thickness of a single clay particle with the aid of nearly 100%. For example a 10 Å clay mineral can expand to 19Å in water. The amount of shrinkage varies significantly based on whether the mixing water dries up, as in the wet clay technique, or only the naturally occurring moisture, as in the earth-moist clay method. The shrinkage dimensions are approximately 3–12% for the wet clay method and 0.4–2% for the rammed earth method. The most crucial features of clays in the field of soil mechanics include their hydraulic conductivity, gas conductivity, ion diffusion capacity, swelling potential, compressibility, and rheological properties. The type and amount of clay minerals in the soil, as well as the soil's bulk density, influence all of these characteristics. [27,28]

The electrical charge and colloidal size of clay mineral particles affect their hydraulic conductivity and stress/strain characteristics differently compared to sand-based soils. Smectites, in particular, have extremely small and convoluted pore networks that impede water and gas diffusion, which is more prominent at high densities when the water suction caused by compacted clays exerts a negative pressure. The function of these soils depends heavily on soil-water potentials. Another significant characteristic of clay minerals is their ability to exchange ions, which can be drawn to the clay particle's surface or absorbed by the structure of these minerals. This property of clay minerals allows ions in solution to be fixed on clay surfaces or within internal locations, which can affect all sorts of ions or compounds carrying surface charge, including organic compounds like pesticides. Thus, clays are also useful means of moving pollutants from one place to another and disseminating them extensively. [29]

Clay material surfaces exhibit a powerful attraction to water molecules. A slurry develops when a small amount of clay is introduced to water because the clay is distributed evenly throughout the water. For instance, the paint industry makes use of this characteristic of clay to equally distribute pigment (color) in paint. It would be challenging to blend the paint foundation and color pigment uniformly without clay to serve as a carrier. Also, clay mixed with water and formed into mud can be molded into various shapes and hardened to create rigid solids, which are utilized by the ceramics industry to produce different types of products such as plates, cups, basins, and pipes. This molding process allows for creative expression, enabling potters and ceramicists to create unique and artistic pieces. By controlling the amount of water in the mixture, the mud can be shaped into specific forms and then fired at high temperatures to produce a durable final product. [30]

When earthen construction materials dry out they become hard but when they absorb moisture they become soft again. As a result, clay construction materials are entirely recyclable and reversible. The dried-out clay, on the other hand, must be protected from moisture, which is best accomplished by structural measures (foundation, splash water protection in the base region, roof overhang) or proper plaster surface treatment. Clay is an exceptionally durable building material when handled properly by professionals. Moreover, clay is a material that stores heat and has a regulating effect on humidity. It has a great storage effect and is thus ideal for use with low-temperature heating systems since it absorbs and distributes heat evenly. [31]

2.4 Construction with clay

Clay construction has a long history worldwide and throughout Europe, and it was traditionally one of the principal construction materials but has since been superseded by contemporary industrial building materials that are "half-timbered but also solid wearing." This indicates that these buildings were constructed using a technique called half-timbering, where a wooden framework is filled with materials such as clay. This combination results in a structure that is both aesthetically appealing (with exposed wooden beams) and durable. Half-timbered houses with clay infill have been common in Europe since the Middle Ages, from France over Germany to Eastern Europe. Although mudbrick construction was the most popular, other mud construction methods such as Wuzel masonry, "g'satzte construction," rammed earth, and ashlar block masonry were also utilized. In today's homesteads, you will typically discover a combination of diverse earth construction techniques and burnt bricks due to multiple conversions and extensions. Buildings built of cob, a clay-straw mixture, can be found in Germany and France, but mainly in the United Kingdom (Devon, Cornwall, and Wales), where an active cob house movement is dedicated to conserving the numerous historical specimens. Industrial earthen construction materials are becoming increasingly essential in today's world, and they have the benefit of being able to be employed on any building site without requiring additional processing time or effort. Above all, the use of dry construction methods has many benefits over the use of wet construction methods, including simplicity of implementation, a shorter building period, improved thermal and acoustic insulation, moisture resilience, and fire safety. [32]

Earthen construction materials are now available commercially in a variety of ways because clay is found in practically every place, so ensuring that the clay comes from the local area is rather simple. Also, there are currently a variety of prefabricated pieces available, many of which are associated with wood. Mud structures in Europe have to fulfill a variety of standards owing to the temperate environment, which includes harsh winters and occasionally significant rainfall. In many areas, wood was a plentiful resource, and the use of wood as a structural element and adobe as an infill medium was common. In certain areas where wood was scarce, rammed earth or cob walls predominate, which, because of their massiveness and superior storage effect, were able to withstand even harsh winters. [33]

2.4.1 Construction with rammed earth

In the realm of sustainable construction, clay-based materials have gained significant attention due to their environmental friendliness, abundance, and durability. One of the most enduring clay-based construction materials is rammed earth. This technique involves compacting specialized soils to create robust walls. Rammed earth can be utilized in two ways: as building blocks or in the construction of entire walls, layer by layer. To create the blocks, soil is pressed into a mold resembling a box, utilizing wooden planks separated by a spacer bolt. These blocks are then stacked, and more earth is rammed in to achieve the desired wall height. The ideal soil composition for rammed earth consists of 70% sand and 30% clay, with 10% water added for current usage. This technique results in walls with excellent compressive strength, making them suitable for load-bearing designs. [34]

The earth-building methods are as diverse as the earth deposits found in any location. The most essential and widely used earthen construction methods are briefly outlined here.[8] For the construction of rammed earth walls, stable formwork is necessary. Soil-moist earth is injected in layers and crushed into the formwork. Manual ramming, pneumatic ramming, and vibrating plates are all options for compaction. The naturally available excavated material of clay, sand, and gravel, which is typically well suited for this style of building, is a benefit of rammed earth. Retailers now sell a variety of rammed earth combinations in massive quantities. [35]

Clay construction techniques such as the Weller-Clay method have gained popularity in Lower Austria due to a scarcity of stone in the region's clay deposits. The Weller-Clay method involves stacking and shaping layers of a loam-straw mixture with little to no aggregate content. [36]

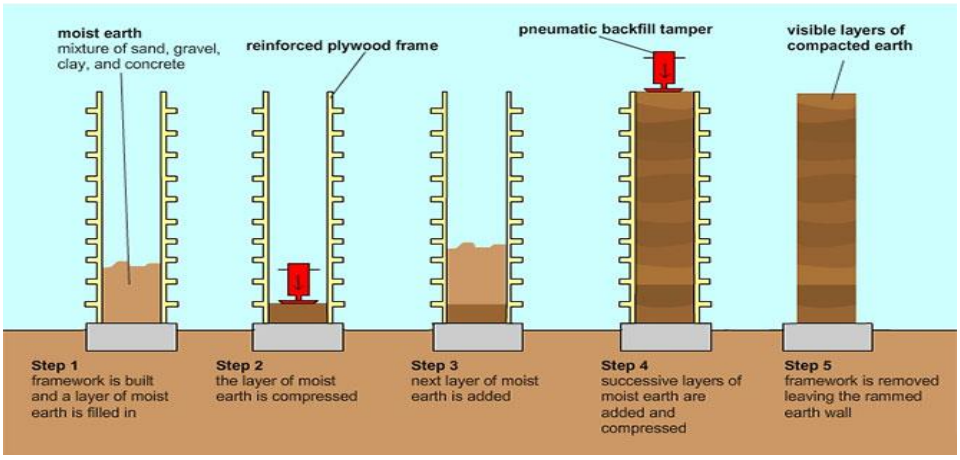


Figure 4: The beginning and development of rammed earth technology in environmental design.

The extrusion molding method, which is prevalent in the brick business, is used to industrially fabricate unfired clay bricks. Green compacts are the name for the resultant bricks because of their high raw density and susceptibility to moisture. They are mostly employed in non-load-bearing parts of interior construction. They may absorb temperature peaks and regulate the room's moisture because of their large storage mass. Clay bricks are offered in a variety of forms, bulk density classifications, and additives in today's market. Construction planning earth structures and earth components should be designed in such a manner that they provide permanent weather protection as well as constructive moisture protection. Earth components must be protected from the elements even during the building process. [37]

2.5 History of the use of clay

Clay is one of the world's oldest construction materials. Already hunters and gatherers built basic defensive structures out of wood coated in clay long before people settled down. Earth-building civilizations can be found all throughout the world, and in numerous areas, many people still live in earthen structures. Clay structures may still be found in great concentrations today, particularly in hot and dry climatic zones. In these regions, resources such as wood and stone are typically rare, and furthermore, the adobe constructions' large bulk keeps the interiors cool, which makes them ideal construction and building materials. [38]

While the Romans used a lot of stones and burned bricks in their architecture, they also employed air-dried mud bricks and timber frame structures with wattle and daub for minor buildings. The Romans utilized rammed earth in timber and stone-poor locations, such as basic material on the lower Rhine. The Xanten Archaeological Park, for example, shows a rammed earth reproduction of a Roman home. This clay construction method has been practiced throughout Europe for millennia. Industrialization brought new transportation routes with it in the second part of the nineteenth century. As a result, coal became widely available, and brick kilns sprang up all throughout, for instance, Lower Austria. Simple field kilns were originally constructed, which were typically excavated into existing loess rocks, subsequently, ring kilns were constructed, which could be continually charged and so had a considerably larger capacity. This marked the beginning of the end for adobe buildings, which were progressively supplanted by burned bricks and eventually faded away over the twentieth century. [39]

2.6 Applications and benefits of building with clay

Clay was gradually rediscovered as a healthy and ecologically acceptable construction material in the early 1980s. When used in Central Europe, however, it must be shielded from the weather because it only hardens physically rather than chemically, as most other construction materials do. [40]
The positive attributes of clay in the construction sector include its versatility, energy efficiency, durability, visual appeal, economic stability, and a natural characteristic of clay that means clay is a natural material with inherent benefits; it's non-toxic, free from harmful chemicals, and does not emit VOCs [Volatile Organic Compounds, are a group of organic chemicals that have a high vapor pressure at room temperature], contributing to a healthier indoor environment. Its natural origin also makes it a sustainable and environmentally friendly choice. [41]

The production of industrial construction materials is known for its high energy demands, highlighting the need for alternatives that are both energy and resource efficient. Assessing the full life cycle of a structure, along with its associated CO_2 emissions, is crucial to achieving a positive energy balance. In this context, earthen construction emerges as a logical and straightforward choice. Clay, a frequently excavated material, offers numerous advantages as a construction material, including its ability to be reused and eventually returned to nature when no longer needed. A key benefit lies in the widespread availability of clay, enabling the construction industry to maintain shorter transportation routes. Unlike traditional materials such as concrete, brick, and plasterboard, earthen construction materials do not require energy-intensive processing. Consequently, clay exhibits a significantly better CO_2 balance, making it an environmentally favorable option for construction purposes. [42]

Clay offers several benefits for creating a healthy interior environment, and it has moisture-regulating properties that help improve the indoor climate by intelligently managing humidity levels. This prevents excessive moisture, which can lead to mold growth and negatively affect health, as well as excessively dry air that can cause respiratory issues. Clay is especially beneficial for individuals with neurodermatitis, allergies, or asthma. Additionally, earthen construction materials are often free from harmful compounds. In arid climates with extreme temperature variations, clay walls provide temperature compensation by absorbing heat during the day and releasing it gradually at night, ensuring more balanced and comfortable room temperatures. Furthermore, clay is soundproof and can be used to create soundproof walls when combined with other construction materials. [43]

Clays, including brick loam, because of their high heat storage qualities, are suited as raw materials for firing bricks, like other heavy building materials, and can be used for hot components. This permits, for example, high-flow floor and wall heating systems with heating pipes plastered below the operating temperature. Clay is an incredibly versatile material with remarkable properties, and it has the unique ability to rapidly absorb moisture as well as heat and then release it when necessary. This characteristic makes clay highly efficient at regulating humidity and temperature, providing a natural and sustainable solution. Moreover, clay is an abundant resource, found in ample quantities worldwide, making it a readily available option. Its widespread availability and simplicity of handling contribute to its appeal as a sustainable material. Unfired clay, in its pure form and without any additives, is a completely natural substance that can be gathered from the environment and returned to it without causing harm. The inherent reusability of clay further enhances its sustainability profile. By simply adding water, clay can be easily reshaped or crushed with minimal effort, allowing for indefinite reuse. This perpetual cycle of usage and renewal underscores the longevity and resource-conserving nature of clay as a material. [44]

3. 3D printing of clay

Since clay is a natural substance, its physical and chemical properties differ from one deposit to another and throughout all of its sources. For injection 3D printing, clay can be used directly after cleaning and dispersion in water, or it can be combined with other additive materials. "3D printing of clay in building construction, often referred to as 'clay 3D printing' or 'ceramic 3D printing,' is an innovative technology that leverages 3D printers to create architectural structures and building components using clay-based materials, offering a range of advantages in design flexibility, sustainability, and construction efficiency". [45]

Here is a breakdown of how clay 3D printing works and its key features:

1. Material: the primary material used in clay 3D printing is a clay-based mixture that typically includes clay, water, and sometimes additives or binders to improve its properties. This mixture needs to have the right consistency to be extruded by the 3D printer.

2. 3D printer: specialized 3D printers are used for clay 3D printing. These printers have a nozzle or extrusion system that deposits the clay material layer by layer, much like how traditional 3D printers work with plastics or metals.

3. Layer-by-layer deposition: the 3D printer follows a digital design or CAD (Computer-Aided Design) file,

extruding clay material layer by layer to build up the desired structure. The process is additive, meaning material is deposited only where needed, reducing waste compared to subtractive construction methods.

4. Design freedom: one of the main advantages of clay 3D printing is the design freedom it offers. Architects and designers can create highly intricate and customized structures, including complex geometries, curved shapes, and patterns that may be difficult or expensive to achieve using conventional construction methods.

5. Sustainability: clay is a natural and sustainable building material. Using clay in 3D printing reduces the environmental impact associated with traditional construction materials like concrete and steel. Additionally, the minimal waste generated during the printing process contributes to sustainability.

6. Speed and efficiency: clay 3D printing can be a faster construction method compared to traditional bricklaying or concrete pouring, especially for certain designs. It reduces labor requirements and can potentially shorten construction timelines.

7. Strength and durability: printed clay structures can be strong and durable, but their properties depend on the specific clay mixture used, the printing process, and post-processing techniques like drying and firing.

8. Post-Processing: after printing, the clay structure may need post-processing steps, such as drying and firing in a kiln, to enhance its strength and durability. These steps can also affect the final appearance and texture of the structure.

9. Applications: clay 3D printing has various applications in building construction, including creating walls, facades, partitions, ornaments, and even entire buildings. It is important to note that clay 3D printing is a developing technology, and its adoption in the construction industry is still in its early stages. Researchers and companies are continually working to improve the materials, processes, and scalability of this innovative construction method. As it matures, it has the potential to revolutionize how we build structures, offering sustainable, efficient, and architecturally creative solutions to construction challenges. [46]

3.1 Methods for 3D printing of clay

In this section, exploring various methods for 3D printing clay for building construction are discussed.

1. Fused Filament Fabrication (FFF):

FFF 3D printing, also known as fused deposition modeling (FDM), involves extruding clay material through a nozzle, layer by layer, to build up the final object. The clay filament is heated and extruded onto a build platform, where it cools and solidifies to form each layer. This method is similar to traditional plastic FFF 3D printing but adapted for clay-based materials.

2. Selective Deposition Lamination (SDL):

SDL 3D printing uses sheets or layers of clay that are cut into the desired shape and bonded together layer by layer. A machine typically applies adhesive or heat to fuse these clay layers together. This method is akin to laminating sheets of paper to create a 3D object.

3. Stereolithography (SLA):

SLA 3D printing employs a liquid clay resin as the base material. A UV laser or projector is used to selectively solidify the liquid resin layer by layer, creating a solid object as each layer hardens. SLA is known for its high precision and detailed output.

4. Binder Jetting:

In binder jetting, a clay powder is spread in a thin layer, and a liquid binder is selectively deposited onto the powder to bind it together in the desired pattern for each layer. This procedure is repeated for every layer till the 3-d item is complete. Binder-jetting is often used for creating ceramic objects.

5. Ceramic Extrusion Printing:

Ceramic extrusion printing is similar to FFF, but it's tailored specifically for clay materials. Clay is pushed or extruded through a nozzle onto the build platform, where it forms each layer of the object. This method is commonly used for pottery and ceramic art.

6. Powder Bed and Inkjet Head 3D Printing (PBI):

PBI 3D printing utilizes a clay powder bed as the base material. An inkjet print head selectively deposits a liquid binder onto the powder to bind it together, layer by layer. The excess, unbonded powder acts as support material, which can be removed after printing.

7. Robotic Arm 3D Printing:

This approach involves the use of robotic arms equipped with clay extruders to create large-scale clay sculptures. The robotic arm can precisely control the deposition of clay to build complex shapes and structures.

Each of these methods offers different advantages and is suitable for various applications, ranging from art and sculpture to ceramics and architectural prototypes. The choice of method depends on factors like the desired object's size, complexity, and material properties. These methods collectively offer a wide range of possibilities for artists, designers, and manufacturers, pushing the boundaries of creativity and functionality in ceramics and pottery. As technology continues to evolve, clay 3D printing is expected to bring even more innovations to this field. [47]

3.2 Benefits of 3D Printing with clay

The use of 3D printing in construction includes faster building processes and the capacity to produce intricate shapes using reduced amounts of material. However, the lack of building standards recognizing the technique and physical characteristics of the printed components represents a challenge. 3D printing with clay is considered as a sustainable and cost-effective approach to construction, which can reduce material waste and carbon footprints. The technology can also provide greater than accuracy, design flexibility, and durability when creating intricate and complex shapes. The overall benefits of 3D printing with clay in construction can lead to faster than more sustainable, cost-effective, and flexible construction processes. 3D printing of clay is an innovative method that combines 3D printing technology with clay-based materials for building construction. Overall, 3D printing of clay has the potential to revolutionize architectural design and construction practices. [48]

4. Aims and objectives

The aim of this project was to investigate and develop clay-sand formulations with suitable characteristics and flow behavior (viscosity) for 3D printing and extrusion. The purpose of this study was to provide some useful metrics for determining what qualities are ideal for clay 3D printing. Initial tests include determination of the appropriateness of earth as a construction material for usage in the fields of tamping, printing, prefabrication, and in conjunction with other materials. Mixtures based on two distinct types of clay and sand should be made for this purpose and their drying, shrinkage, and warping behavior, as well as the dimensional stability of formulations should be investigated. Furthermore, the mechanical characteristics of dried components should be investigated, and ejection and casting experiments with optimum formulations should be conducted. An appropriate production method needed to be developed to create a well-proportioned mixture of clay with specified values of sand and water, which would enable using rammed earth as a building material.

5. Experimental section

5.1 Materials

Clay was provided by Claytec and two types of clay were used as the starting material: rammed earth natural 02.004 ("BL") and rammed earth fine 02.008 ("BLF"). According to the manufacturer, the grain size is "natural" (0–16 mm) and "fine"(0–8 mm) (oversize up to 22 or 16 mm is possible), respectively. The Dry raw density is approx. 2,300 kg/m^3 and the shrinkage is "0.5%"(natural) and "0.7%"(fine). Two types of sand were used as additives: quartz sand ("Q-sand", Knauf Quartz Sand 0.1–0.5 mm grain size, bulk density 2,622 kg/m^3) and play sand ("S-sand", "Children's Play Sand", Herzer Sand- und Kieswerk). Tap water from the 9th district of Vienna was used in all experiments.

5.2 Chemical evaluation of the raw ingredients

X-ray photoelectron spectroscopy (XPS/ESCA) was used to examine the chemical composition of the various clay and sand types. XPS was performed on a NEXSA system (ThermoFisher) with Al Kα radiation at 72 W and a pass energy of 200 eV, a spot size of 400 µm, "Standard Lens Mode," and CAE Analyser Mode. An energy step size of 1 eV for the survey spectrum (20 passes) and an integrated flood gun were used. Samples were analyzed before and after the surface was treated with Ar clusters (1000 Ar atoms, 6000 eV, 60 s). The high-resolution spectra (step size 0.1 eV) of the single elements were acquired with 20 passes at pass energies of 50 eV. Peak analysis was performed with Thermo's Advantage software v5.9925 Build 06702.

5.3 Experimental methods and procedures

Two types of clay and sand were combined. The initial drying tests were conducted using clay-water suspensions containing between 10% and 70% clay. In addition, sand substituted 25%, 50%, or 75% of the clay content when the clay level was between 50% and 70%. Utilizing a hand mixer, the liquids were homogenized typically in 200 g batches. In the following phase, smaller batches were made in 50 mL Falcon tubes with vigorous stirring and shaking, for viscosity measurements and strand generation using a syringe.

5.3.1 Drying behavior of clay BL 10 to 70% with water mixture

To examine the drying/shrinking behavior, 200 g (120 g for mixtures with a larger proportion of clay) of the produced mixture were divided into two or three equal portions and placed into plastic Petri dishes. The initial composition involved blending clay (BL) and water in a ratio of 10 to 50%, resulting in a total mixture of 200 g. Subsequently, 50 g aliquots were dispensed into three petri dishes and the mixtures were allowed to undergo drying at room temperature. Mixtures of 60% and 70% BL with water were made with 120 g and 50 gr portions were distributed into three containers. The samples were subjected to weight measurement after both one day and one week. The mass loss was then evaluated after one day and one week.

5.3.2 Drying behavior of clay BLF 30 to 70% and water mixture

For BLF 30 to 70% BLF in water were prepared, constituting a total mass of 120 g. Notably, this time, the samples were divided into two containers, each containing 50 g of the mixture. The containers were placed at room temperature and weighted after intervals of one day and one week.

5.3.3 Drying behavior of clay BL and BLF 25 to 75% with Q-sand and water mixture

BL and BLF with Quartz sand were mixed in varying proportions specifically, 25%, 50%, and 75%, with water comprising 50% of the overall composition. The total mass of each mixture was standardized at 120 g. A quantity of 50 g from each mixture was dispensed into two separate petri dishes. Following the established procedural framework, these petri dishes were left at room temperature for a week. Subsequently, the weight of each sample was precisely measured.

5.3.4 Standard drying vs. Oven drying

In a distinct phase of the experiment, blends of BL or BLF with water were prepared, in ratios of 55%, 60%, and 65% to 45%, 40%, and 35%, respectively. The cumulative mass of the entire mixture was standardized at 160 g. Initially, 50 g aliquots were dispensed into three separate containers and positioned at room temperature. Subsequently, equal portions of 10 g each were carefully extracted using a syringe. One subset was placed in a container maintained at room temperature (22°C), while the other was placed in an oven at approximately (70°C). Weight measurements were systematically recorded after intervals of one hour, one day, and one week. This methodology facilitated a comprehensive analysis of the drying behavior, allowing for a comparative assessment between samples subjected to room temperature and those exposed to elevated oven temperatures.

5.3.5 Dimension stability

During this phase, mixtures comprising BL and BLF were formulated with varying proportions of 55%, 60%, and 65%, combined with water at ratios of 45%, 40%, and 35%. Additionally, different proportions of S-sand and Q-sand, namely 25% and 50%, were integrated into the mixtures. Throughout these procedures, apart from conducting weight measurements at three designated intervals (one hour, one day and one week), a small segment of the samples was excised after the one-week period. Utilizing a caliper, the diameter of each segment was meticulously measured, enabling a comparative analysis of dimensions.

5.3.6 Viscosities of the formulations

Formulations for viscosity were analyzed using a TA rheometer (XYZ) in plate-plate geometry, with a 50 mm diameter and a gap size of 1 mm. Viscosities were analyzed in rotational mode between shear rates of 10 s^{-1} and 100 s^{-1}.

5.3.7 Ejection experiments for viscosity measurements by using rheometry

For ejection experiments ratios of BL and BLF to water were adjusted to clay (50-60-62-65-68%) and 70% water (40- 30%). Special attention was also given to the ratio of Q-sand relative to the quantity of BL. Each sample was standardized to a total mass of 100 g. These experiments were extracted using a syringe and carefully transferred to designated containers. After extraction via syringe, these samples were meticulously deposited into Falcon tubes.

5.3.8 Mechanical properties of dried formulations

Compression tests were performed on a minimum of five specimens for sample at 25 °C and 40-45% RH using a dual column universal test frame (Instron Model 5969, Darmstadt, Germany) equipped with a 1 kN load cell at 1 mm/s. Specimens (diameters approx. 15 mm, heights approx. 3 mm) were shaped from suspensions dried in Petri dishes.

5.3.9 Demonstration of "printing" and assessing dimensional stability

Using a pneumatic syringe, formulations with an 80% solids content made up of 3/4 BL and 1/4 S sand were ejected into the strands, shaped into various 3D objects, and dried for a week. For this experiment, a higher viscosity was required to compensate for the higher pressure at which ejection is performed in this application. Even in their dried form, the threads displayed great dimensional stability.

Another demonstrator for the suitability of investigated material formulations was the preparation of solid bricks from the developed formulations. The experiment involved casting hollow bricks from a mixture containing 80% solid content, with a composition of ¾ BL soil and ¼ S-sand. During the casting process, issues arose with adhesion to the mold and cracks in thicker-walled areas. To address these problems, an experiment was conducted to understand the cause of the cracks and found that the high adhesive properties of the BL soil were responsible. By increasing the proportion of S-sand in the mixture, it was discovered that the drying behavior improved, resulting in reduced adhesion and fewer cracks in the finished bricks. This adjustment in the mixture's composition, helped mitigate brittleness and improve the quality of the hollow brick components.

6. Results and Discussion

6.1 Chemical composition of the raw materials

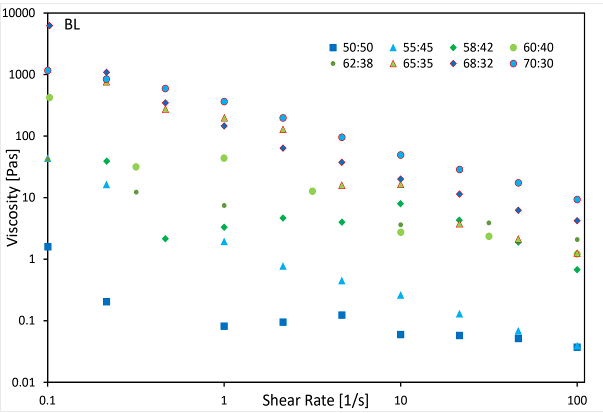
The primary elements in both types of clay are oxygen, nitrogen, and aluminum, with iron, magnesium, calcium, and potassium serving as subsidiary constituents. The found amounts of carbon and nitrogen are caused by surface impurities. The same holds true for minute amounts of phosphorus, sodium and chlorine. There was slight variation between the two types of sand, with S-sand having greater Ca, Mg, and Fe concentrations and S-sand having lower a Si content.

Table 1: Basic surface composition of the various clay and sand types employed.

Element	Atomic Fraction [at.-%]		Element	Atomic Fraction [at.-%]	
	BL	BLF		Q-sand	S-sand
O	61.23	61.63	O	61.62	62.14
Si	17.28	17.71	Si	21.99	16.80
Al	9.31	9.43	Al	8.15	10.06
C	5.68	5.48	C	5.19	4.19
Fe	2.50	1.87	K	1.47	1.47
Mg	1.14	1.19	Ca	0.71	1.36
Ca	1.00	1.02	Mg	0.39	1.32
K	0.98	1.05	Fe	0.25	2.67
N	0.53	0.33			
P	< 0.20	< 0.20			
Cl	< 0.20	< 0.20			
Na	< 0.20	< 0.20			

6.2 Viscosity of water-clay (-sand) formulations

The rheological properties, i.e. the viscosity, was measured as a function of shear rate. In rheological measurements, the shear rate is a critical parameter that reflects the level of mechanical stress applied to a material. The results of viscosity measurement as function of shear rate are shown in Figure 5. To ensure the required stability after processing and shape retention, a formulation should have a viscosity of more than 50 Pas to up to over 1000 Pas (measured at a shear rate of 1 s^{-1}). Suitable processability is achieved at a viscosity of up to about 20 Pas (at 100 s^{-1}). It is evident for BL and BLF that there is a strong shear-thinning flow behavior present and the viscosity is highly dependent on the solids content, as expected. The behavior of shear thinning is a notable fluid property that demonstrates how viscosity decreases when exposed to high shear rates. For the finer BLF particles, a more homogeneous flow pattern is observed, while the larger particles of BL result in stronger deviations from double-logarithmic linearity. Upon visual inspection, it was discerned that compositions with 10 and 20% clay (BL and BLF) content exhibited remarkable smoothness, indicative of exceptionally low viscosity. This characteristic deemed them unsuitable for assessment using a rotary rheometry device. At low shear rate (1 s^{-1}) viscosities of almost 10000 Pas were observed for suspensions containing the highest clay contents. Beyond 50 % clay content low-shear viscosities of about 50 Pas were attained, fulfilling the requirement for low shear rates. With increasing shear rates, the viscosity almost linearly (in double-logarithmic scale) dropped to viscosities < 1 Pas for clay contents < 60%. For clay contents between 60 and 70% the viscosities were between 1 and 20 Pas at high shear rates. In general, a trend was observed that BLF exhibited higher viscosities than BL over all shear rates and clay contents owing to the finer particles and thus higher specific surface area present. . Notably, samples characterized by higher water content, specifically those with a 55% BL ratio, exhibited larger diameters, indicative of heightened viscosity. Furthermore, samples prepared with Q-sand displayed increased fragility in comparison to those incorporating S-sand. This heightened fragility posed challenges in measuring the diameter of certain samples due to their brittle nature. This observation underscores the influence of sand type and water content on the physical properties of the samples, particularly in relation to viscosity and fragility.



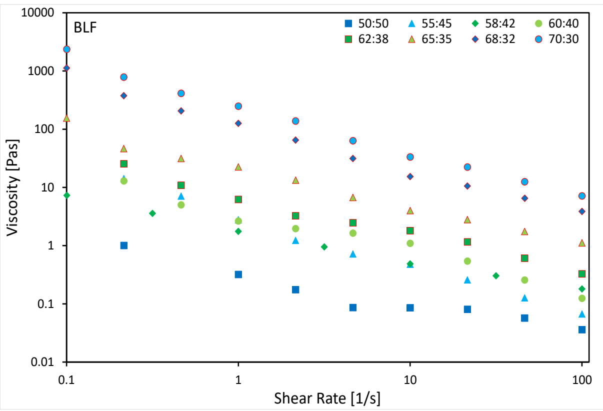


Figure 5: Viscosity is a function of the shear rate for BL (left) and BLF (right) formulations of contents BL and BLF:water.

6.3 Shrinkage and drying characteristics

Figures (6) exemplarily show suspensions immediately after pouring into Petri dishes (a) and after drying for one week (b). It was observed that for some samples drying caused stresses resulting in cracks whereas for lower clay contents rolling up of the discs was observed.

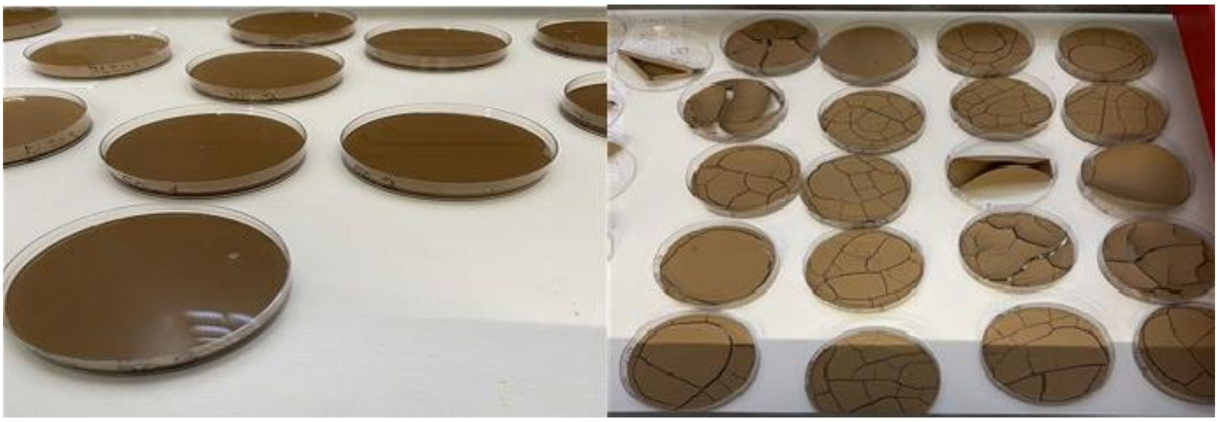


Figure 6: Photographs of (a) mixtures in petri plates (left) and (b) dried mixtures one week later (right).

In Figure 7 images of the BL and BLF samples are shown after drying for one week. It was found that the drying behavior as well as shrinkage and warpage are all strongly influenced by the clay content. Mixtures containing 50 to 70% BL had completely dried after one week. However, samples tended to crack because of the drying stresses were developed with BLF formulations being more prone to cracking than BL formulations. On the other hand, up to a clay content of merely 30%, samples showed considerable warpage, i.e. they “rolled up”, because of one-sided drying caused by differences in the drying between bottom and top. In between those regions, i.e. at 40% to 50%, BL samples exhibited favorable drying characteristics with minimal cracking and fragility. By contrast, even at these concentrations, BLF samples were prone to higher levels of fragility and cracking than BL samples. These studies reveal that in order to make high-quality molded components, it is crucial to consider both the clay content and the layer thickness generated.

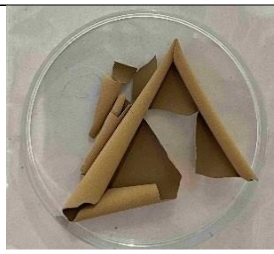
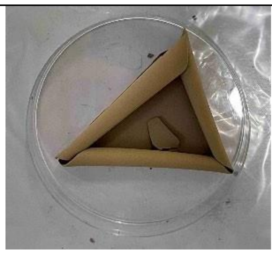
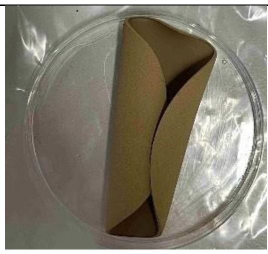
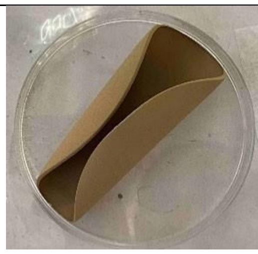
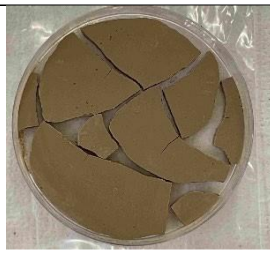
Material/Clay-Content	BL	BLF
10 %		-
20 %		-
30 %		
40 %		
50 %		
60 %		
70 %		

Figure 7: Photographs of the dried BL and BLF formulations.

The drying behavior of the dispersions was also quantified (Table 2). Dry masses observed for clay concentrations below 100 % can be attributed to the fact that the initial clay was not completely dry. It was further found that even after one day of drying at room temperature (22 °C), a minimum of 20% water (based on the clay´s initial mass) remains present, even in samples with the highest contents of clay. The data suggests that beyond 40% clay content formulations could be prepared with sufficient homogeneity to yield well dried samples after one week.

Table 2: Drying behavior of BL and BLF: relative mass of the dispersions in relation to the initial solid content.

Clay-Content	BL		BLF	
	1 Day	1 Week	1 Day	1 Week
10 %	823 %	55 %	-[1]	-
20 %	410 %	78 %	-	-
30 %	280 %	91 %	280 %	94 %
40 %	207 %	89 %	212 %	89 %
50 %	169 %	100 %	169 %	100 %
60 %	142 %	100 %	143 %	100 %
70 %	120 %	99 %	122 %	101 %

In order to mitigate the effect of warpage and shrinkage induced cracking, sand was added to the formulations. This step is integral in elucidating the influence of diverse clay and sand ratios on the weight characteristics of the samples over the course of a week. Sand is less prone to water uptake and dimension-variations as compared to clay and hence should provide stability during drying. Figure 8 shows the drying behavior of formulations (50% solids/50% water) in which 25, 50, or 75% of the clay phase have been substituted with Q-sand. Whereas at low sand content (25%) smooth samples were obtained, at medium and high sand content crack formation increased again because of the property of sand that it does not form cohesive structures when dry. In contrast to BLF also in blends with sand, BL exhibits a less brittle drying behavior similar to the behavior of pure clay. When compared to formulations using Q-sand, the drying behavior with S-sand tends to be yield brittle samples. (Figure 9)

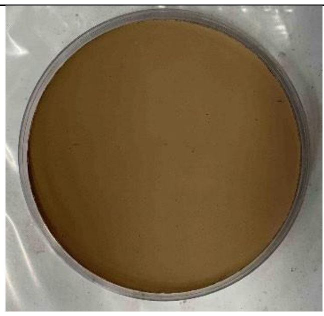
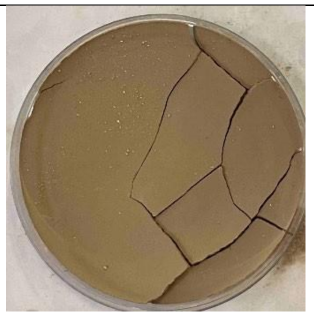
Material/Sand-Content	BL	BLF
25 %		
50 %		
75 %		

Figure 8: Photographs of 50% dry content formulations of BL and BLF with 25, 50, or 75% S-sand in the solid phase.

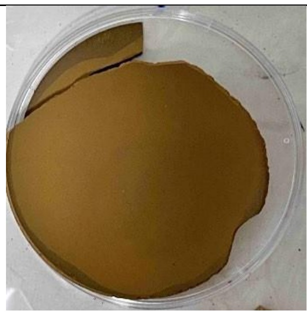
Material/Sand-Content	BL	BLF
25 %		
50 %		
75 %		

Figure 9: Photographs of the 50% dry content formulations of BL and BLF with 25, 50, or 75% S-sand in the solid phase.

6.4 Dispersion stability during drying of ejected strands

For 3D printing applications the rheological behavior is a key indicator. From viscosity measurements suitability of formulations was assessed. However, also the ejectability and stability of ejected strands is important in terms of practical application. A suitable technique used to assess the behavior of the dispersions is the syringe method, which involves subjecting the material to shear forces during ejection and investigating the stability of the shape upon drying. Moreover, the appearance of the dried strands indicates suitability of the formulation in the application.

Formulations with a clay content of between 30 and 75% were shaped into a strand from a syringe and the stability of the shape was assessed as a test for shaping/printing (Figures 10 & 11). All of the formulations exhibited suitable viscosities low enough to allow for processing, meaning that they can all be manually forced out of the syringe at high shear rates. However, below a solids content of 50%, it was discovered that BL and BLF formulations exhibited too low viscosities to maintain their shape and appropriate dimensional stability following processing. These results indicate the optimal compositional range for samples created using a syringe and dried at room temperature for a week. Furthermore, above 70% solid content samples tend to become brittle as they dry. Based on these findings, it was concluded that the optimal soil content for stable and non-brittle molding is between 60 and 70% providing well balanced stability and flexibility.

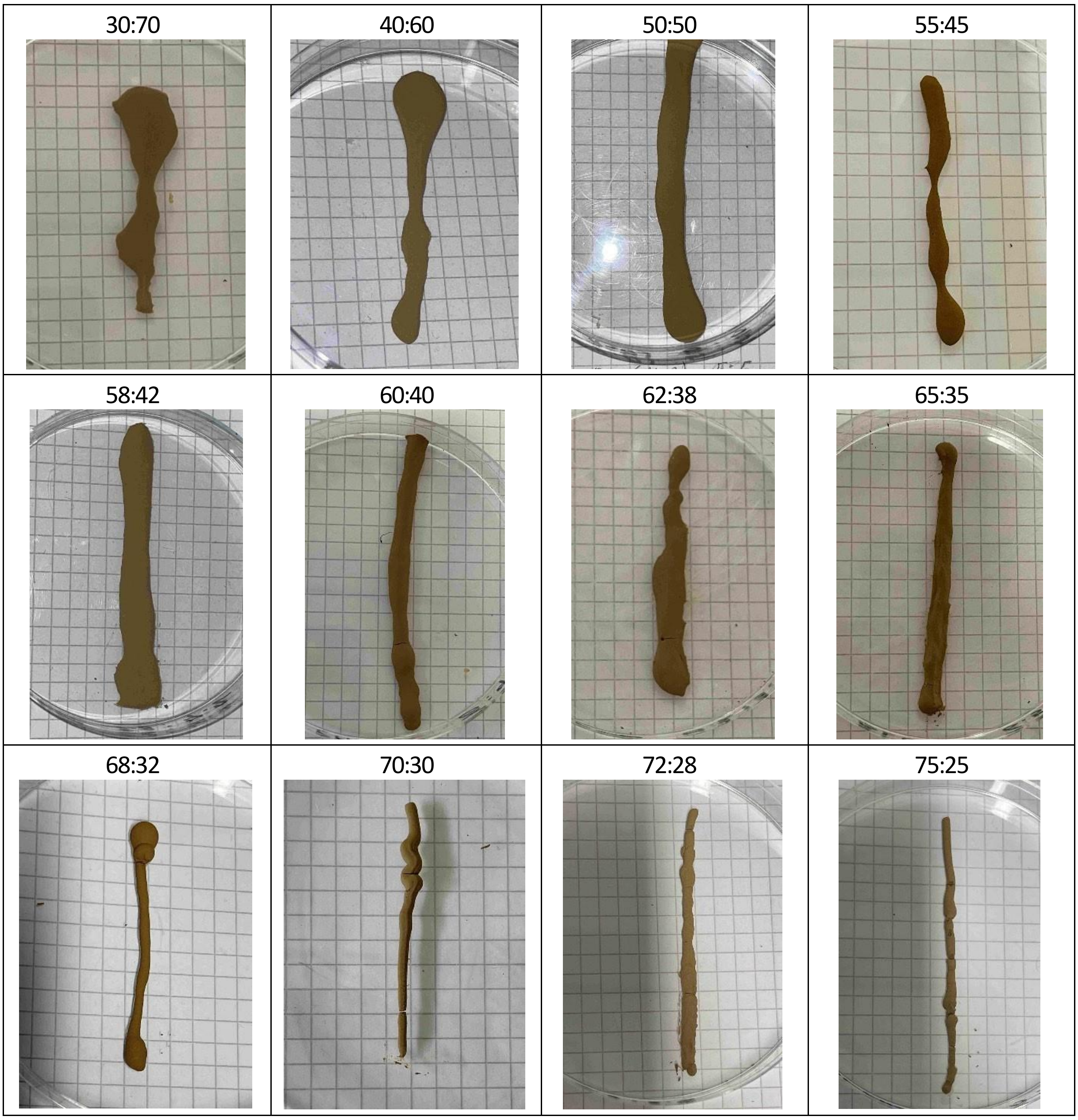


Figure 10: Photographs of 30 to 70% solids content ejected BL formulations after one week of drying.

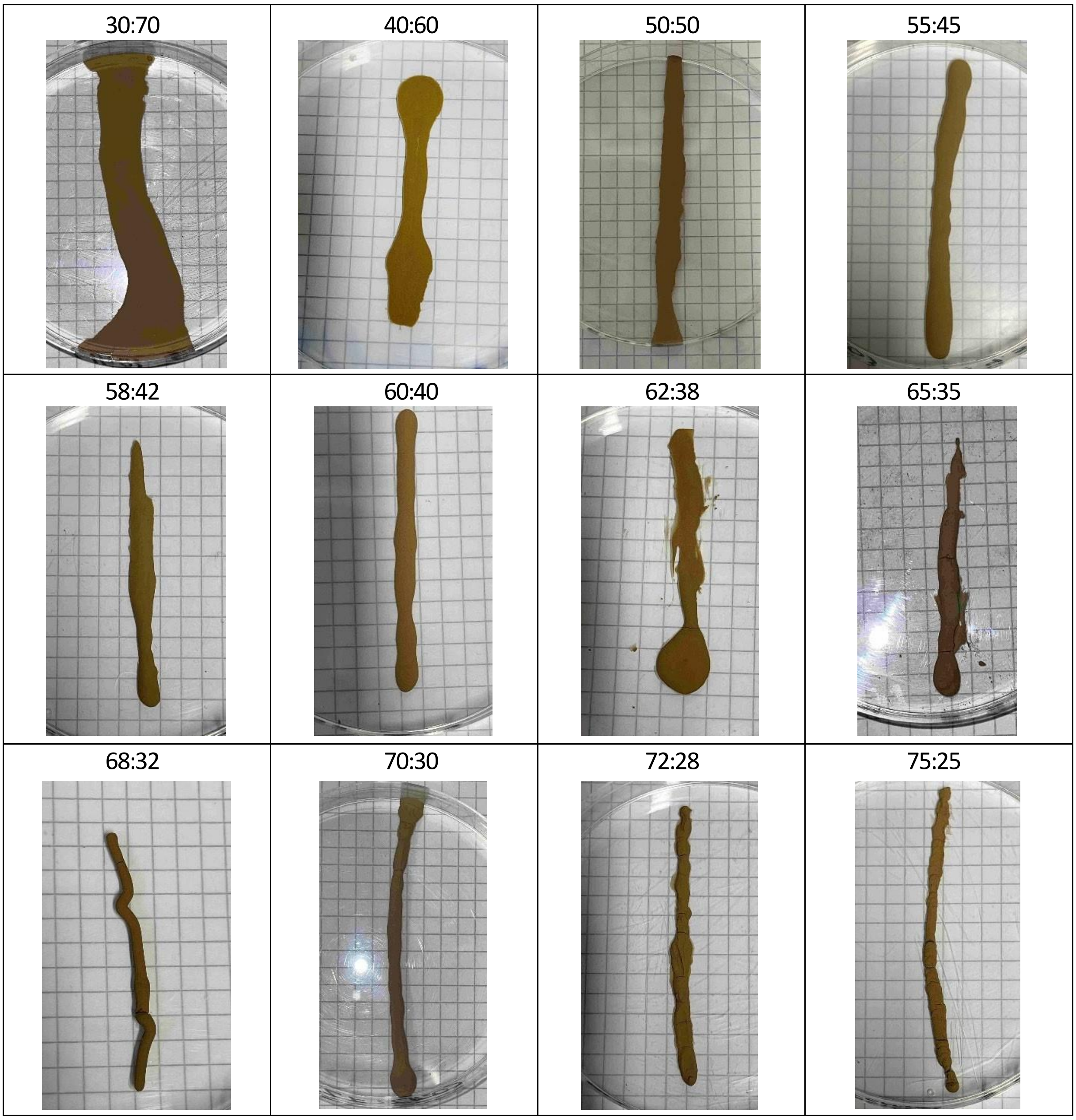


Figure 11: Photographs of 30 to 70% solids content ejected BLF formulation after one week of drying.

Following the determination of the ideal clay content, which was between 60% and 70%, Q-sand was added to the BL and BLF formulations in proportions of 25%, 50%, and 75% of the total solids content (Figure 12). Also here, the goal was to create stable forms with consistent dimensions. To evaluate dimensional stability, formulations with Q-sand as part of the solid phase were created with 30 to 40 % water content (60 to 70% solids content). Strands were then ejected using a syringe. It was found that sand can contribute up to 50% of the solids phase at a total solids concentration of 70% without compromising dimensional stability. In other words, in order to maintain structural stability, the amount of sand in the solids phase must not exceed around one-third of the total suspension.

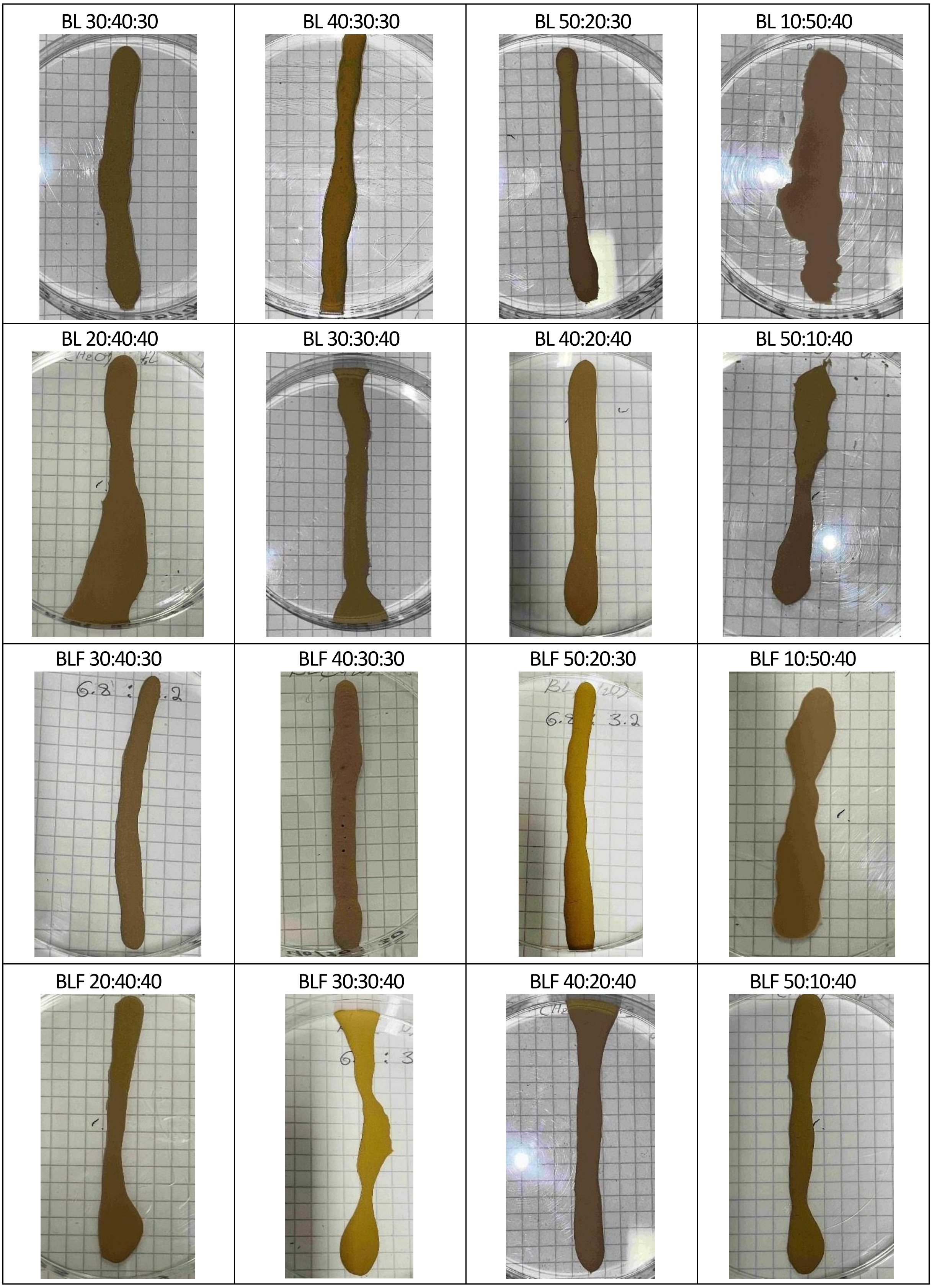


Figure 12: Photographs of the sprayed and dried formulations of BL and BLF with solid content levels of 60 to 70 % and Q-sand. BLF: Sand : Wasser.

6.5 Compressive strength of dried formulations

Samples with a solids content of 55, 60, and 65%, of which 0, 25, or 50% were Q- or S-sand, respectively, were subjected to compression tests. Results of compression tests are displayed in Figure 13 in terms of compressive strength. The compressive strength of the BL and BLF samples derived from formulations with 55%, 60%, and 65% solid content was almost the same with a slight tendency to higher strength for thicker formulations, in particular for BL. Interestingly, BLF exhibited lower impact of its content, whereas for BL the trend of higher strength for higher contents was more pronounced. Thus, whereas BLF samples had higher strength at 55%, at higher fractions BL samples were stronger. These differences were ascribed to differences in the particle size and distribution of the clay.

However, upon addition of sand the mechanical behavior started to shift and differed between the samples. When 25% play sand was introduced, the tensile strength of the 65% BL sample was significantly higher than that of the 55% and 60% solid content formulations, with the 55% and 60% samples exhibiting very little difference.

With the addition of 25% S sand, a reduction in tensile strength was to be accepted for various BLF contents. However, for 25% and 50% S sand the impact and reduction in tensile strength was almost the same. The first chart shows that the reduction in tensile strength with 50% S sand is significant only for 60% BL soil, while it is not substantial for other soil percentages.

According to the first chart, with the addition of 25% S sand, a reduction in tensile stress is observed in BL soil. The impact and reduction are relatively consistent. On the other hand, addition of 25% S-sand had a smaller impact on the strength of BLF compared to BL but further addition of sand resulted in an additional decrease, opposed to BL. In the end, the compressive strength of both BL and BLF formulation with 50% S-sand was almost the same.

Adding 25% and 50% Q sand to BL and BLF soils at 55%, 60%, and 65%, respectively, exhibited distinctly different results to S-sand. Addition of 25% Q-sand to BL formulations had a relatively small impact and none at all for 65% BL. However, 50% Q-sand resulted in strengths only a quarter to a third of the original value for pure BL. For BLF the trend was largely the same but to a considerably smaller degree. It was concluded that the use of Q-sand in fractions of 25% had the smallest impact on the mechanical performance of both BL and BLF samples, respectively, but beyond this share Q-sand caused a dramatic decline of mechanical strength. For S-sand, on the other hand, there were some sweet spots, usually at higher overall solids content where result materials exhibited appropriate mechanical strength.

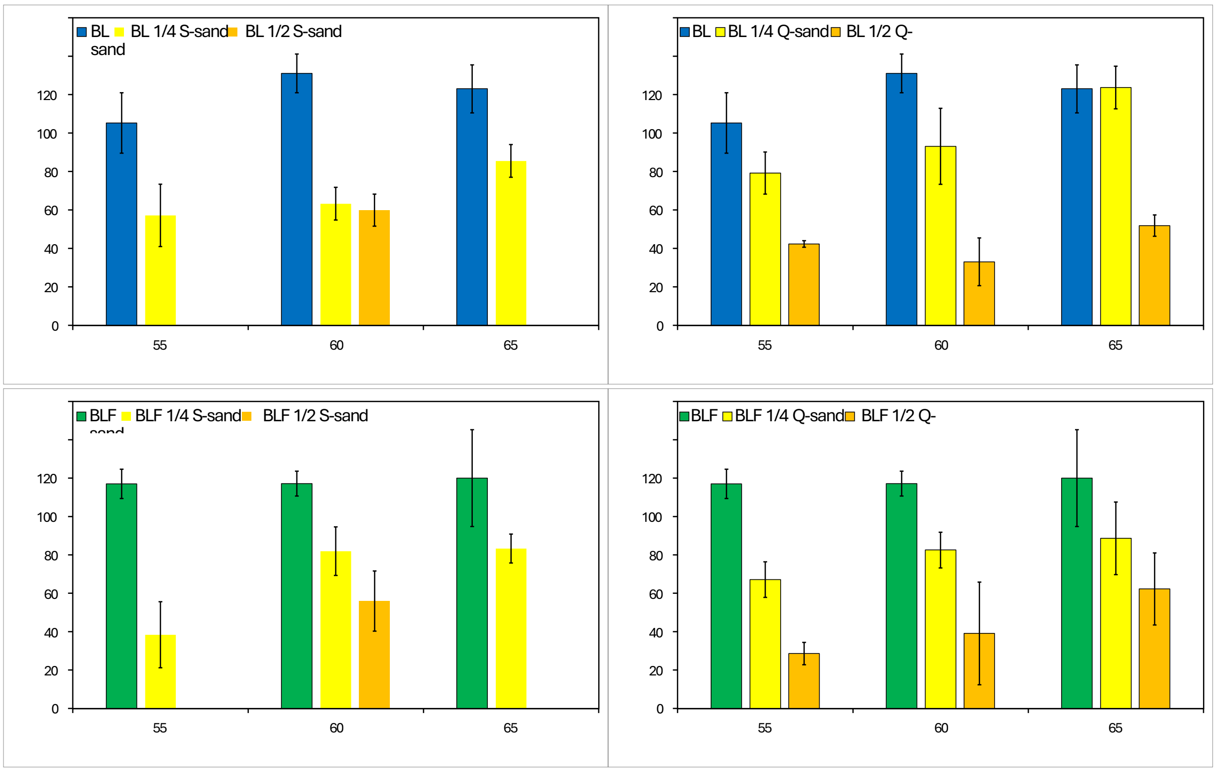


Figure 13: Compressive strength of dry BL or BLF formulations with S-sand or Q-sand

6.6 Demonstration and dimensional formulations of clay

Casting tests conducted using a "hollow brick mold" have demonstrated the ability to produce thick-walled parts effectively when the right formulation is used. However, challenges arise with the molding of the core, which cannot be accomplished without causing damage. Additionally, the clay tends to adhere to the outer mold.

Figure 14: 80% solids content pneumatically sprayed, and dried strands (¾ BL und ¼ S-sand).

During the casting process, issues arose with adhesion to the mold and cracks in thicker-walled areas. To address these problems, an experiment was conducted to understand the cause of the cracks and found that the high adhesive properties of the BL soil were responsible. By increasing the proportion of S-sand in the mixture, it was discovered that the drying behavior improved, resulting in reduced adhesion and fewer cracks in the finished bricks. This adjustment in the mixture's composition, helped mitigate brittleness and improve the quality of the hollow brick components. [Figure 15]

Figure 15: Thick-walled bricks casted from 80% solids content formulations (¾ BL und ¼ S-sand).

7. Conclusions

The aim of this work was to reveal that clay content significantly affects the drying behavior, shrinkage, and warpage of molded parts and strands. Low clay content (below 40%) can cause severe distortion, like "curling," due to one-sided drying. Homogeneous discs could be produced from formulations with 40-50% clay, while higher clay content led to cracking due to tension from thickness and one-sided drying. Both clay content and layer thickness are critical for high-quality molded parts. Replacing part of the clay with sand showed similar drying behavior to pure clay of low sand contents (25%), but higher sand content made the material more brittle. Dried BL formulations less brittle than BLF, and those with S-sand were less brittle compared to Q-sand formulations. The viscosity characteristics, drying behavior, shrinkage, and warping of flat-molded components are significantly influenced by the clay content. When the clay fraction in the suspension is low (<40%), one-sided drying causes significant deformation and the samples "roll up". At high clay fraction (>50%), the samples were strained during drying due to their thickness and one-sided drying generating cracks. For the creation of high-quality molded products, both the clay content and the layer thickness generated are crucial factors.

The viscosity and drying behavior of mixtures of clay, water, and two types of sand (Q-sand and S-sand) were tested. Formulations with too low viscosity were unsuitable for printing, requiring a solids content above 50% for effective printing. However, solids content above 70% led to fractures during drying due to strains from asymmetric drying. Sand can be added up to 25% of the solid content, and for more formulation up to 50%, within which the mechanical characteristics of the materials were analyzed. Although adding sand reduces compression performance, ideal formulations were identified where this impact is minimal. Generally, adding more than 25% sand relative to the clay content results in low mechanical performance and brittle drying behavior. When sand was added to clay formulations to counteract shrinkage and act as a filler, the effects on material properties were studied. Formulations with 25% sand showed drying behavior similar to pure clay, but higher sand content increased brittleness during drying. Compared to BLF (presumably another formulation), BL showed less brittle drying behavior, with or without added sand. It was found that sand could constitute up to 50% of the solid phase at 70% solid content without compromising dimensional stability. However, at 40% water content (60% solids), the sand content in the solid phase needed to be limited to about one-third to maintain dimensional stability.

In order to demonstrate the pumping system for 3D printing, formulations were dispensed using a pneumatic syringe. The viscosity of the formulations had to be adjusted accordingly, and they contained up to 80% solids, predominantly consisting of ¾ BL and ¼ S-sand. These strands maintained excellent dimensional stability both during drying and in the dry state, allowing for the successful production of stable strands. However, it was observed that a pneumatic silicone syringe was not ideal for continuous printing, as the strand formation occurred intermittently rather than at a constant speed. As a result, further investigation into rheology additives would be beneficial for future experiments, particularly when using industrial 3D printers. Casting tests with the "hollow brick mold" have demonstrated that, with the right formulation, thick-walled molded pieces may be created, but the core cannot be de-molded without being destroyed and that the clay tends to stick to the outside mold. De-molding spray might be a suitable solution to this issue. Analyzing the desiccation activity throughout the vertical sample cross-section is alike challenging.

Tests for pouring and spraying with improved formulas were successful, with sprayed strands retaining their form until dry. Hollow bricks and solid cuboids were produced, but more testing is needed to ensure bricks meet construction standards and don't crack in thick walls.

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Abstract

A fair share of the world's population resides in houses constructed wholly, or mostly, of silt and rammed earth. As many as 40 distinct earthen construction styles are utilized. Additionally, digitally based earthen building techniques have been used in the field of construction, particularly for the use of clay-based materials. Recently, 3D printing by extrusion deposition has received the greatest attention among these methods. In the present study, the material properties of clay and rammed earth for application as building materials in modern housing construction by 3D printing were investigated and the applicability of 3D printing to earth-based materials is evaluated. Initially, earthen materials' rheological behavior was investigated to determine suitable compositions acceptable for 3D printing. The viscosity and drying behavior of dispersions of two types of rammed earth content (natural and fine clay) in water with sand were studied. Below 50% clay content, the viscosity at rest was too low for fabricating a stable structure after printing. On the other hand, upon drying formulations with more than 70% clay content, substantial cracking developed due to strains caused by asymmetric drying. To compensate for shrinkage and warpage during drying, addition of various types of sand were evaluated. Sand contents of more than 25% of the total solids fraction resulted in decreased the compression strength, typically yielding poor mechanical characteristics and drying behavior. However, some optimal formulations were identified where this impact was minimal. Thus, sand can be added to up to 25% of the solids content and in certain formulations up to 50%. Extrusion and ejection experiments were successfully completed using optimized formulations. Optimized strands kept their shape during drying. Laboratory-scale printing was performed, and printed samples have been mechanically evaluated. Also, massive cuboids (hollow bricks) could be produced, demonstrating the efficiency of clay and sand formulations for use in 3D printing and molding applications.

Kurzfassung

In der vorliegenden Arbeit wurden die Materialeigenschaften von Lehm und Stampflehm für die Verwendung als Baumaterial im modernen Wohnungsbau durch 3-D-Druck untersucht. Die 3-D-Drucktechnik mittels Extrusion hat dabei die größte Aufmerksamkeit erhalten, und wir bewerten die Möglichkeit, sie auf erdbasierte Materialien anzuwenden. Es wurde das rheologische Verhalten von Lehm-Suspensionen für den 3-D-Druck getestet und getrocknete Formulierungen mechanisch bewertet. Die Viskosität und das Trocknungsverhalten von Dispersionen von zwei Arten von Stampflehm (natürlicher und feiner Lehm) in Wasser mit Sand wurden untersucht. Bei einem Lehmgehalt von weniger als 50 % war die Viskosität zum Drucken zu niedrig. Andererseits entwickeln sich bei Formulierungen mit einem Lehmgehalt von über 70 % beim Trocknen erhebliche Risse aufgrund von Spannungen durch asymmetrisches Trocknen. Um die Rissbildung zu vermindern kann Sand bis zu 25 % des Feststoffgehalts und in bestimmten Formulierungen sogar bis zu 50 % hinzugefügt werden. Sand verringerte die Druckfestigkeit, jedoch wurden einige optimale Formulierungen identifiziert, bei denen dieser Einfluss minimal ist. Sandgehalte von mehr als 25 % des Feststoffgehalts weisen schlechte mechanische Eigenschaften und Trocknungsverhalten auf. Extrusion und Auswurfversuche wurden erfolgreich mit optimierten Formulierungen durchgeführt. Die optimierten Stränge behielten ihre Form während des Trocknens bei. Es konnten auch massive Quader (Hohlziegel) produziert werden, was die Effizienz von Lehm-/Sandformulierungen für den Einsatz in 3-D-Druck- und Formanwendungen zeigt.

Appendix

Drying of BL and BLF mixtures after one day and one week was observed. The reported percentages represent the proportion of remaining mass relative to the initial weight of the clay.

Table 5: Drying behavior of samples with55-65% Bl or BLF clay after one day and one week: relative mass of the original dry mass.

Clay-Content	BL		BLF	
	1 Day	1 Week	1 Day	1 Week
55 %	147 %	100 %	149 %	100 %
60 %	136 %	101 %	130 %	95 %
65 %	130 %	101 %	121 %	100 %

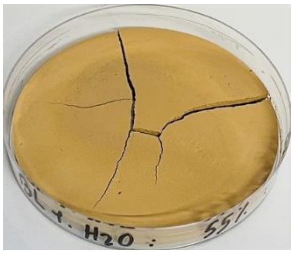
Material/Clay-Content	BL	BLF
55 %		
60 %		
65 %		

Figure 17: Photographs of sprayed and dried BL and BLF formulations (a solids content of 50 to 65 % BL : BLF: Water).

Table 6: Drying behavior of samples with 55-65% Bl or BLF clay with 25% Q-sand after one day and one week: relative mass of the original dry mass.

Clay-¼Q-sand-Content	BL		BLF	
	1 Day	1 Week	1 Day	1 Week
55 %	149 %	110 %	153 %	109 %
60 %	138 %	100 %	140 %	106 %
65 %	128 %	100 %	129 %	102 %

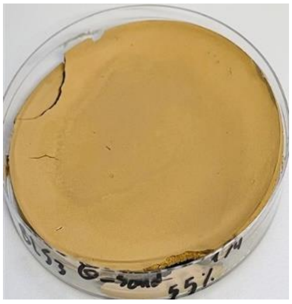
Material/ ¼Q- Sand Content	BL	BLF
55 %		
60 %		
65 %		

Figure 18: Photographs of dried BL and BLF 55, 60, 65 % formulations with 25 % Q-sand in the solid phase.

Table 7: Drying behavior of samples with55-65% Bl or BLF clay with 50% Q-sand after one day and one week: relative mass of the original dry mass.

Clay-1/2 Q-sand-Content	BL		BLF	
	1 Day	1 Week	1 Day	1 Week
55 %	154 %	132 %	156 %	127 %
60 %	140 %	118 %	143 %	117 %
65 %	119 %	106 %	112 %	104 %

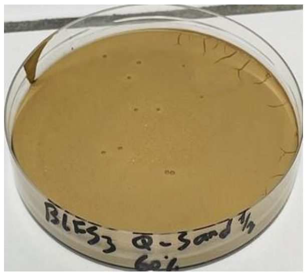
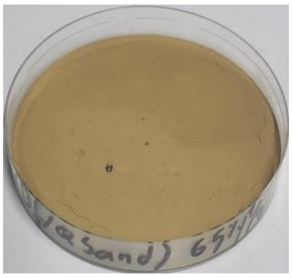
Clay-1/2 Q - Sand Content	BL	BLF
55 %		
60 %		
65 %		

Figure 19: Photographs of dried BL and BLF formulations at 55, 60, and 65 % with 50 % Q-sand in the solid phase.

Table 8: Drying behavior of samples with 55-65% Bl or BLF clay with 25% S-sand after one day and one week: relative mass of the original dry mass.

Clay-¼ S-sand-Content	BL		BLF	
	1 Day	1 Week	1 Day	1 Week
55 %	118 %	118 %	146 %	110 %
60 %	107%	106%	135 %	105 %
65 %	103 %	102 %	110 %	101 %

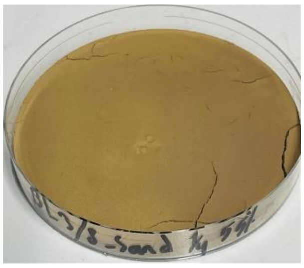
Clay-1/4 S- Sand Content	BL	BLF
55 %		
60 %		
65 %		

Figure 20: Photographs of dried BL and BLF formulations at 55, 60, and 65 % with 25% S-sand in the solid phase.

Table 9: Drying behavior of samples with55-65% Bl or BLF clay with 50% S-sand after one day and one week: relative mass of the original dry mass.

Clay-1/2 S-sand-Content	BL		BLF	
	1 Day	1 Week	1 Day	1 Week
55 %	142 %	138 %	140 %	131%
60 %	129%	117%	126 %	118 %
65 %	114 %	104 %	100 %	106 %

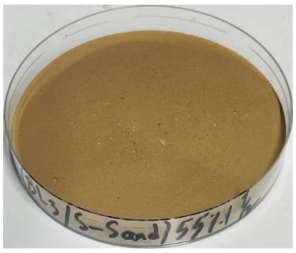
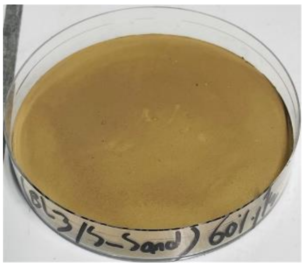
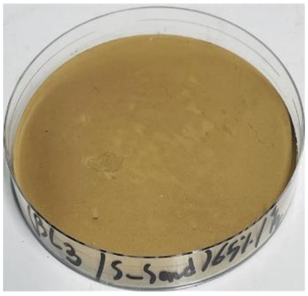
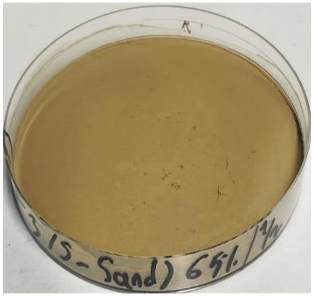
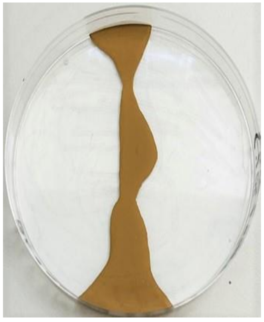
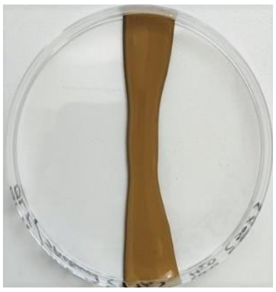
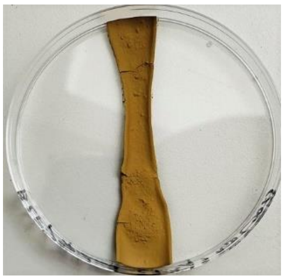
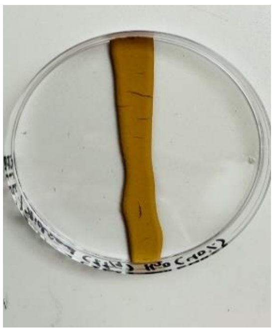
Clay-1/2 S- Sand Content	BL	BLF
55 %		
60 %		
65 %		

Figure 21: Photographs of dried BL and BLF formulations at 55, 60, and 65 % with 50 %S-sand in the solid phase.

BL 45:15:60 	BL 30:30:60 	BL 15:45:60 	BL 54:18:48 
BL 36:36:48 	BL 18:54:48 	BL 63:21:36 	BL 42:42:36 
BL 21:63:36 	BLF 45:15:60 	BLF 30:30:60 	BLF 15:45:60 
BLF 54:18:48 	BLF 36:36:48 	BLF 18:54:48 	BLF 63:21:36 

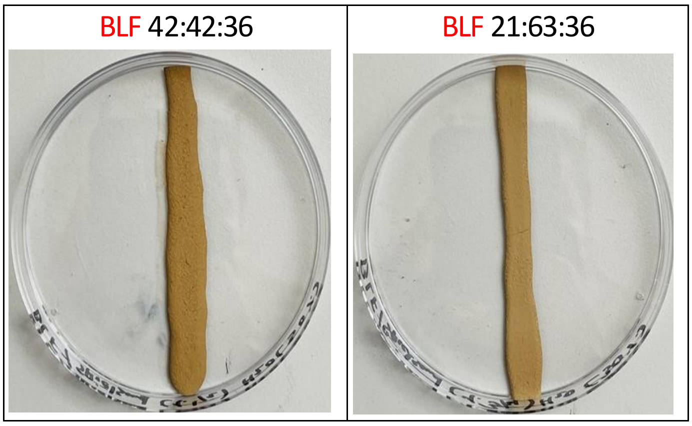


Figure 22: Photographs of ejected and dried BL and BLF formulations with S-sand levels in the solid phase and a solids content of 50 to 65 % (S-sand 50-75%: BL/BLF: 55-65%:Water 50%).

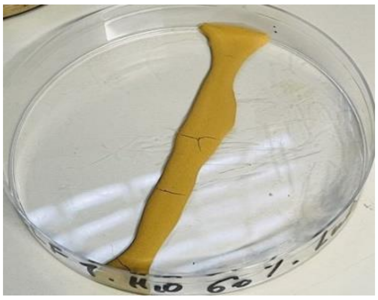
BL: 55:45/Air

BL: 60:40/Air

BL: 65:35/Air

BLF: 55:45/Air

BLF: 60:40/Air



BLF: 65:35/Air

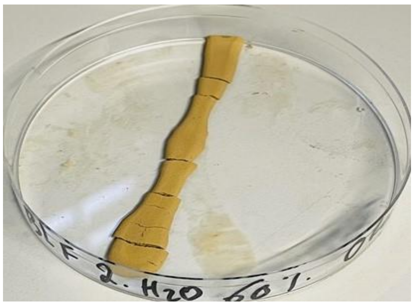
BL: 55:45/Oven

BL: 60:40/Oven

BL: 65:35/Oven

BLF: 55:45/Oven

BLF: 60:40/Oven



BLF: 65:35/Oven

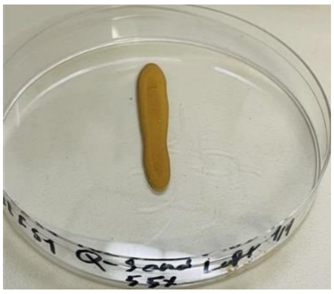
Figure 23: Photographs of BL and BLF 55%-65%, formulations that were ejected, dried, and baked at 70°C in the oven and 25°C outside.

BL: 55:25:45/Air

BL: 60:25:40/Air

BL: 65:25:35/Air

BLF: 55:25:45/Air



BLF: 60:25:40/Air

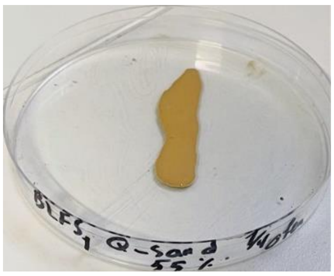
BLF: 65:25:35/Air

BL: 55:25:45/Oven

BL: 60:25:40/Oven

BL: 65:25:35/Oven

BLF: 55:25:45/Oven



BLF: 60:25:40/Oven

BLF: 65:25:35/Oven

Figure 24: Photographs of ejected and dried BL and BLF formulations at 55 to 65 % solids and 25% Q-sand levels in the solid phase. BL/BLF: sand in water at room temperature 25 °C and oven 70 °C.

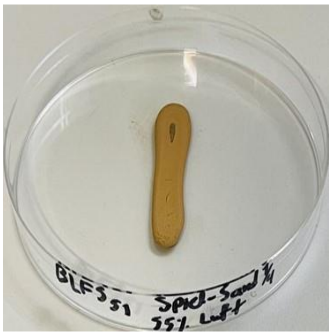
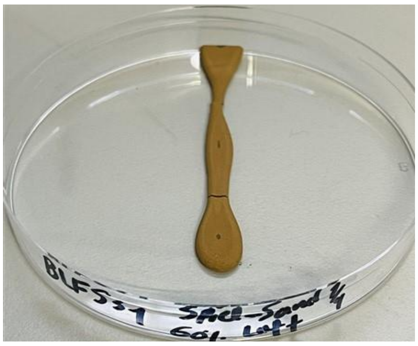
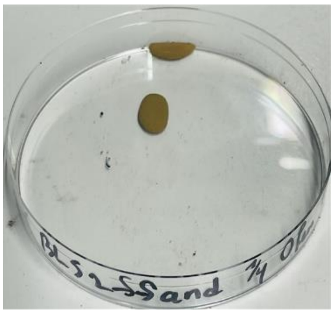
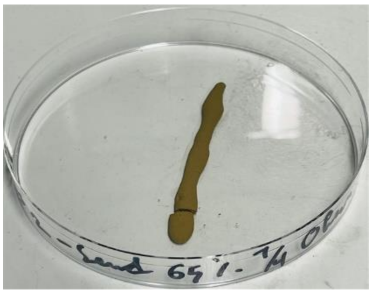
BL: 55:25:45/Air 	BL: 60:25:40/Air 	BL: 65:25:35/Air 
BLF: 55:25:45/Air 	BLF: 60:25:40/Air 	BLF: 65:25:35/Air 
BL: 55:25:45/Oven 	BL: 60:25:40/Oven 	BL: 65:25:35/Oven 
BLF: 55:25:45/Oven 	BLF: 60:25:40/Oven 	BLF: 65:25:35/Oven 

Figure 25: Photographs of ejected and dried BL and BLF formulations at 55 to 65 % solids and 25% S-sand levels in the solid phase. BL/BLF: 1/4 sand in water at room temperature 25°C and oven 70°C.

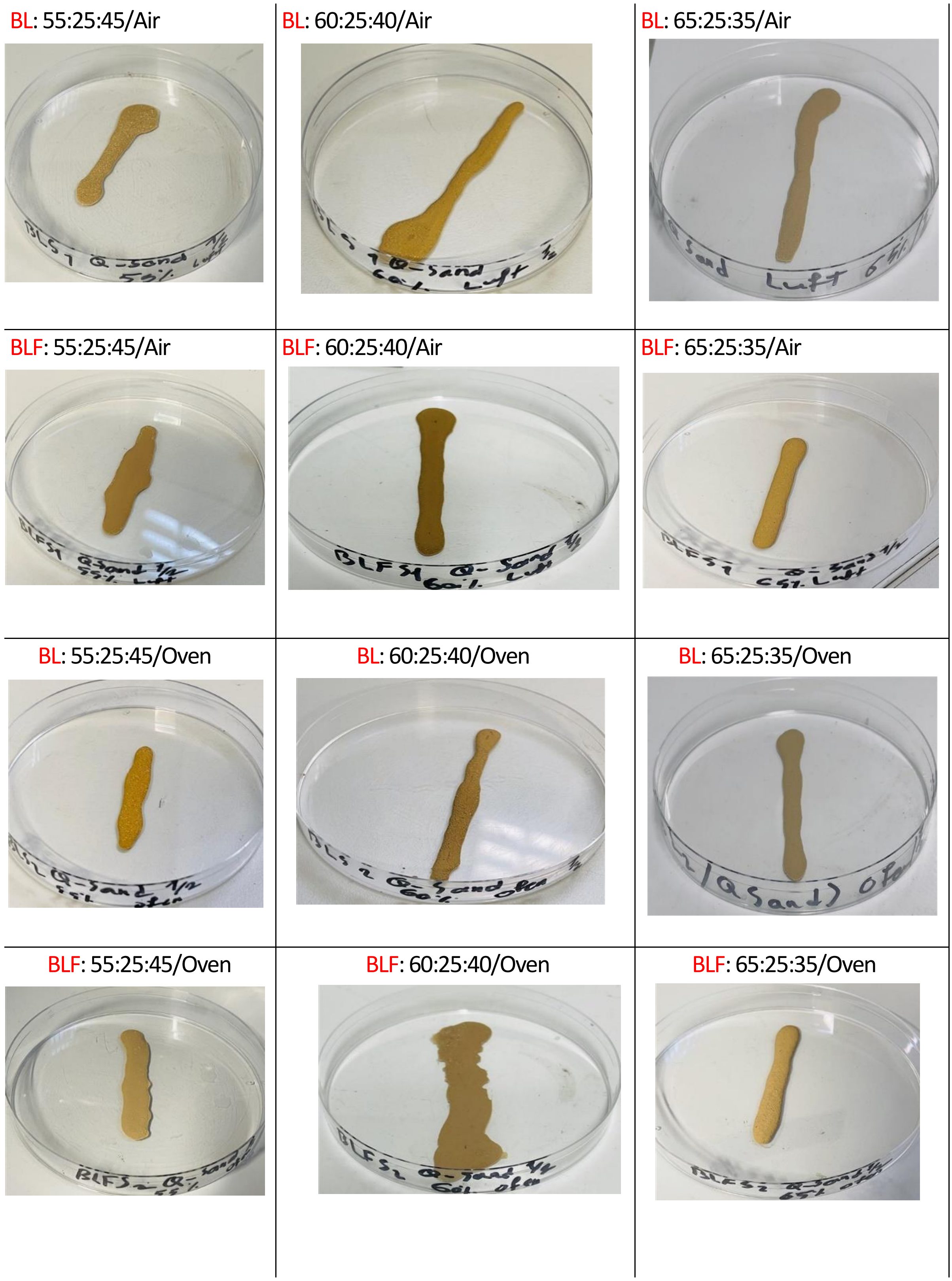


Figure 26: Photographs of ejected and dried BL and BLF formulations at 55 to 65 % solids and ½ Q-sand levels in the solid phase. BL/BLF: sand in water at room temperature 25°C and oven 70°C.

Figure 27: Photographs of ejected and dried BL and BLF formulations at 55 to 65 % solids and ½ S-sand levels in the solid phase. BL/BLF: sand in water at room temperature 25°C and oven 70°C.