Master Thesis
A4 Report

Soil-ed

Sewage derived bio-stabilisers for earth construction

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Abstract

This research investigates the potential of wastewater-derived extracellular polymeric substances (EPS), commercially recovered as Kaumera, as a bio-based stabiliser for earth construction. The study addresses a gap in existing literature concerning the use of secondary biopolymers recovered from wastewater treatment as alternatives to conventional cementitious stabilisers.

A research-through-making methodology was adopted, combining laboratory-scale experimentation with material-driven design exploration. Compressed earth block specimens incorporating EPS in both dry powder and gel form were produced and evaluated through compressive strength testing, water resistance testing, and qualitative assessment of aesthetic and sensory characteristics. Multiple experimental series were undertaken to investigate the influence of binder format, concentration, curing procedures, and soil composition.

The results demonstrate a consistent positive relationship between EPS content and water resistance. Gel-based formulations were particularly effective, with specimens containing elevated EPS concentrations remaining intact after prolonged submersion and significantly outperforming unstabilised controls. Increased EPS content also improved surface quality, reduced drying cracks, and enhanced edge definition. In contrast, compressive strength results were highly variable. While certain gel formulations achieved strength increases of 30-48% relative to baseline samples, subsequent test series produced contradictory outcomes, indicating that strength development is likely influenced by factors not yet established. Dry EPS formulations consistently reduced compressive strength and were therefore considered unsuitable under the tested conditions.

The findings suggest that EPS has considerable potential as a durability-enhancing stabiliser for earthen materials, particularly in applications where water resistance is a primary performance requirement. Proposed applications include erosion protection elements, exterior earth plasters, and earth-based acoustic barriers. Although further investigation is required to understand the underlying stabilisation mechanisms and long-term performance, the research establishes a promising foundation for the use of wastewater-derived biopolymers in circular construction systems.

Key Words Extracellular Polymeric Substances (EPS), Wastewater Resource Recovery, Earth Construction, Biopolymer Stabilisation, Circular Construction

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Table of Contents

01.

Introduction

Pollution, Environment, Water image by Jemzo on Pixabay. Free for use.

Context

*The 2024 United Nations Global Resources Outlook declares a '**triple planetary crisis** of climate change, biodiversity loss and pollution and waste'.*
United Nations Environment Program (UNEP), 2024

As the climate crisis intensifies and resource overconsumption becomes critical, the construction sector is at a turning point. The extraction and processing of materials accounts for over 90% of land use related biodiversity loss and 55% of global greenhouse gas emissions, with the built environment and mobility sectors (excluding energy provision) responsible for more than half of this global material demand (UNEP, 2024). As urbanisation and population growth soars, demand for construction resources will continue to rise (Yu et al., 2023). Global material use has tripled over the past fifty years and, by 2060, may increase by a further 60% compared to 2020 levels (UNEP, 2024). Awareness of the origin and composition of construction materials is therefore paramount, and a paradigm shift in how these materials are sourced, transformed and valued becomes increasingly urgent.

Within contemporary architectural discourse, numerous waste streams that have historically been discarded are reimagined as useful resources – from construction excavation to demolition rubble and industrial by-products. Vernacular and bio-based building techniques are also undergoing renewed interest, with both mass timber and earth construction experiencing a resurgence. These parallel developments present an opportunity to rethink the relationship between waste, material value, and construction through a regenerative lens.

This research situates itself at the intersection of waste-derived material valorisation and earth-based building practices. It investigates the potential of secondary raw materials recovered from wastewater treatment, specifically extracellular polymeric substances (EPS), as bio-based stabilisers for earth construction. By bringing this resource and building system into dialogue, the project explores new forms of sustainable circular materiality and aims to demonstrate how bio-based stabilisation can expand structural and architectural possibilities for an ancient vernacular form of natural building.

Circular Economy and Secondary Raw Materials in Construction

The construction sector has increasingly turned to alternative production and consumption models, most notably the circular economy, as a framework for addressing resource depletion and environmental degradation. Originating in the latter 20th century, the circular economy seeks to decouple economic activity from the consumption of finite resources by transitioning to renewable energy and materials – thus enabling economic prosperity while respecting planetary limits (Ellen McArthur Foundation, n.d.). Rather than relying on a linear extract-transform-dispose model, resources are instead preserved at their highest value and products and materials are circulated in order to eliminate waste and pollution while allowing nature to regenerate.

Within the built environment, circularity is interpreted both as a design strategy – through adaptive reuse, modularity, and design for disassembly – and as a material strategy – favouring renewable materials derived from living organisms (bio-based) or recovered from waste products (secondary) (Circular Buildings Toolkit, n.d.). At a policy level, initiatives under the 2019 European Green Deal, including the New Circular Economy Action Plan (2020), Critical Raw Materials Act (2024) and the New European Bauhaus (revised 2025), explicitly highlight the vulnerability of current material supply chains and promote regenerative, closed-loop construction practices (European Commission, 2020; European Commission, 2024; New European Bauhaus, n.d.).

Secondary raw materials are therefore central to the circular transition, as they enable decoupling of manufacturing processes from extractive practice. Beyond the direct reuse of building components – which remains constrained by availability, performance requirements, and regulatory limitations (Circulariteit: 4 strategieën & de R-ladder, n.d.) – increasing attention has therefore turned towards the development of novel construction materials derived from waste-based feedstocks.

Sewage Sludge as a Biomass Resource

Among available waste streams, sewage sludge (SS) represents a significant yet underutilised source of tertiary biomass. Produced globally at high volumes as a by-product of wastewater treatment – both municipal and industrial – sewage sludge can contain substances that pose environmental risks if improperly managed (Yu et al., 2023). Historically, disposal routes have relied on landfill and incineration, both of which face increasing regulatory, environmental, and economic pressures related to pollution risk, landfill capacity, and carbon emissions. In Europe, SS production is estimated at approximately 9.25 million tonnes of dry solids annually, with countries such as the Netherlands among the top producers (Eurostat, 2022). European Union directives have progressively restricted and even prohibited landfilling of SS while promoting circular waste management principles, driving member states to prioritize recovery and reuse routes over disposal (European Parliament, 2018). According to the latest country profile statistics for the Netherlands the majority of this sludge – 95.6% - is incinerated, while the remainder is largely reused in agriculture or other soil uses (3.9%) and a small amount is landfilled (0.5%) (WISE, n.d.).

Nevertheless, sludge has also long been considered a promising construction material, with the concept traceable as far back as a patent from 1889 (Shaw, T., 1889). Early academic research in the field emerges in the 1980s with Alleman and Bermans work on incorporation of SS in a 'biobrick' (Alleman & Berman, 1984). More recent studies on cementitious and ceramic applications explore SS

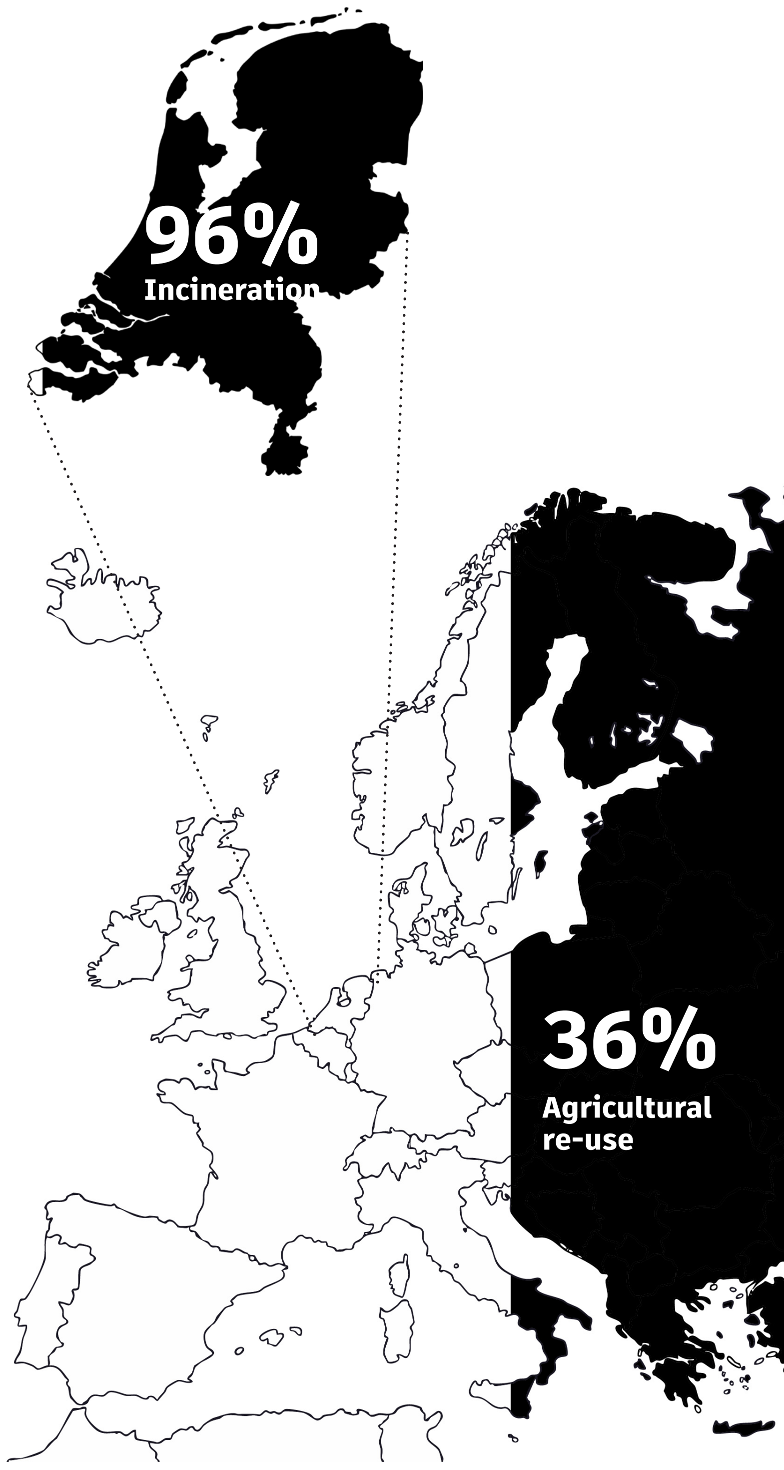


Figure 1. End use and disposal of waste water sludge from treatment plants, as a percentage of total waste water sludge generated. Reproduced from WISE (n.d.)

used as a feedstock for the production of tiles, mortars, pavers, insulating partition blocks, glass and even 3D printed concrete (Yu et al., 2023; Donatello & Cheeseman, 2013; Ki et al., 2021; Ding et al., 2024). However, these approaches largely treat SS as a bulk feedstock rather than a source of high-value functional components.

Recent European research initiatives, including the Interreg-funded WOW! programme (2018–2021) and the Horizon 2020 WATER-MINING project (2020–2024), have shifted focus toward the selective recovery of specific high-performance constituents from wastewater treatment residues. The WOW! project stands for Wider business Opportunities for raw materials from Wastewater (Interreg NWE, n.d.) while the WATER-MINING project aimed to develop sustainable wastewater treatment technologies while promoting 'the extraction of valuable products from the residues generated during the process'(Watermining, 2024). These initiatives have demonstrated the feasibility of recovering valuable materials including cellulose, lipids, and biopolymers from sludge, and signal sustained political and industrial interest in wastewater valorisation.

Extracellular Polymeric Substances (EPS)

A key constituent recovered from biological wastewater treatment are extracellular polymeric substances (EPS), a class of high-molecular-weight polymers secreted by microorganisms. EPS are found in SS deriving from biological treatment methods and form a gel-like matrix that provides structural integrity to the sludge as well as facilitating drying (Hamed et al., 2025). The fraction of EPS termed alginate-like extracellular polymers (ALE) or structural extracellular polymers (sEPS) – which exhibit functional similarities to naturally occurring alginate biopolymers – can make up 20 to 30% by weight of Activated Granular Sludge (AGS) (Duque et al., 2021).

Since 2019, commercial-scale extraction of ALE/sEPS has been implemented at two sites in the Netherlands under the name Kaumera Nereda Gum, after the Nereda wastewater treatment process developed by TU Delft (Kaumera, n.d.). Kaumera extraction reduces sludge volumes while producing a bio-based polymer with diverse functional properties. The specific molecular components can vary but typically include high proportions of polysaccharides and proteins (70–80%) (Hamed et al., 2025). These polymers result in unique material properties, with studies identifying varied characteristics relevant to construction applications, including: water interaction, binding capacity, and fire retardancy (Duque et al., 2021).

To date, however, EPS has primarily been applied in narrow, function specific uses such as cement additives or surface coatings (Duque et al., 2021). In exception to this are several pilot scale projects and academic studies which have explored the integration of Kaumera branded EPS in material composites, namely, rigid compression moulded panels (Sauerwein et al., 2023) and extruded calcite-based elements (MaterialDistrict, 2022). Nevertheless, these experiments have identified major drawbacks relating to durability and odour, leaving a viable commercial application yet to be found.

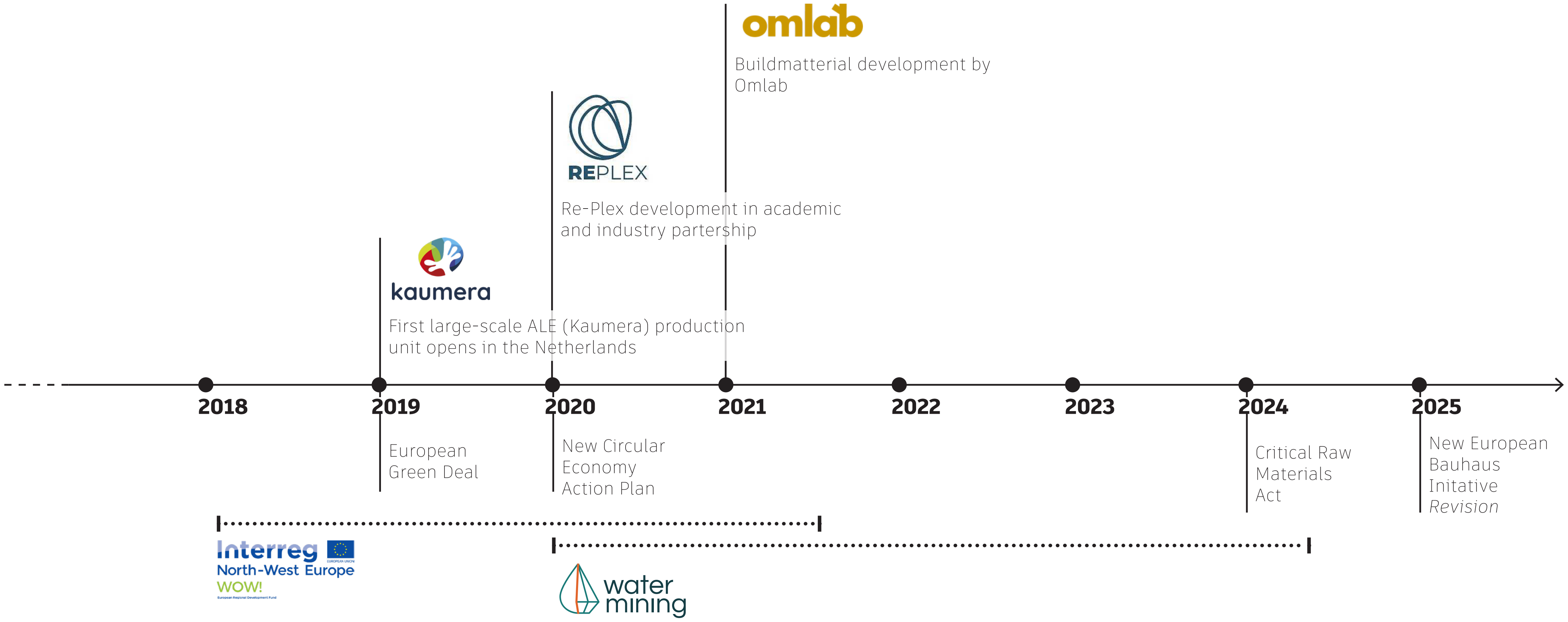


Figure 2. Timeline of EU wastewater valorisation initiatives, using icons & logos from respective organisations. Unaffiliated and not endorsed.

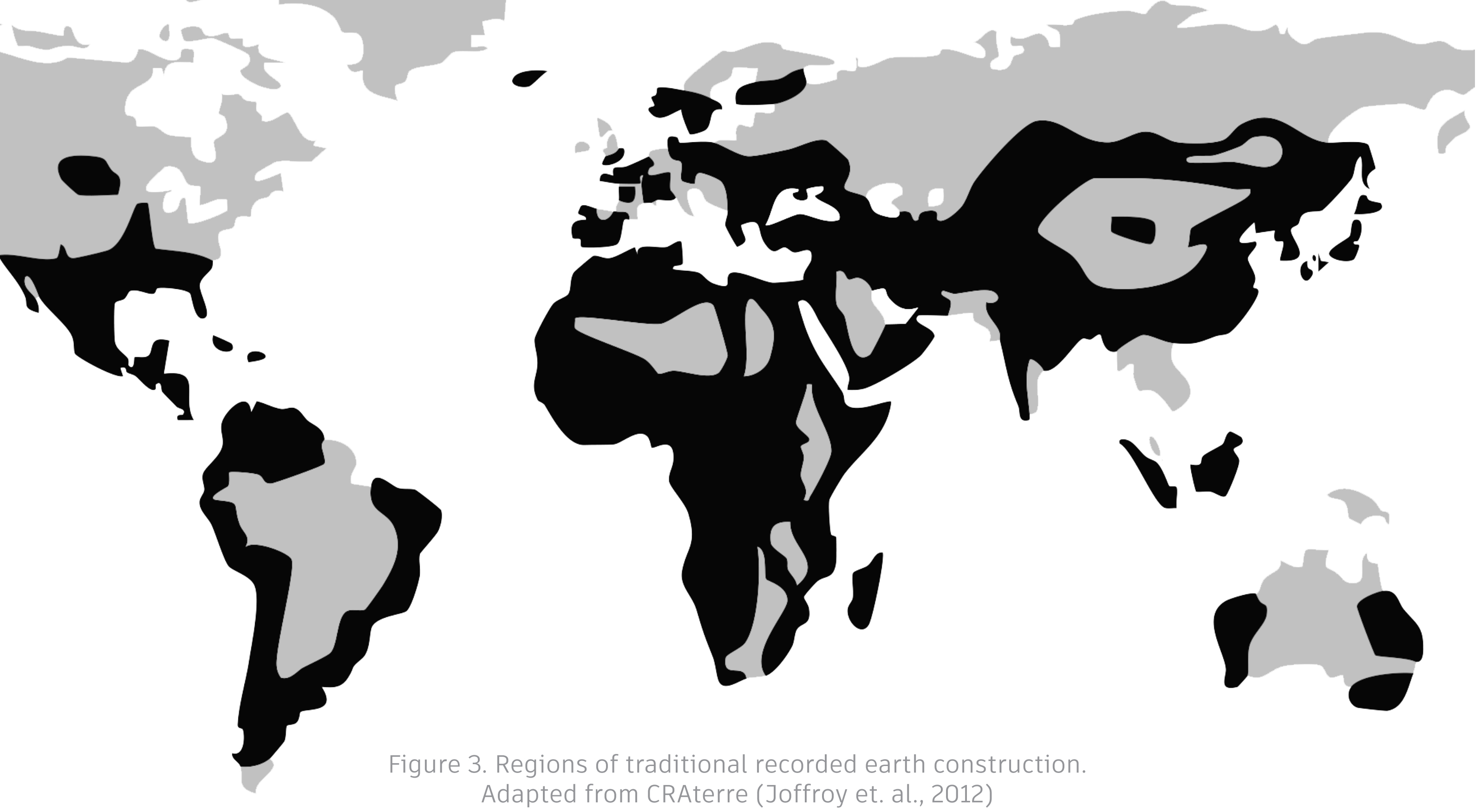


Figure 3. Regions of traditional recorded earth construction.
Adapted from CRAterre (Joffroy et. al., 2012)

Earth Construction and the Limits of Current Practice

Earth construction encompasses some of the oldest known building techniques, including rammed earth, adobe, cob, and compressed earth blocks. These systems rely on locally available soils and minimal processing. They are widely accepted as 'sustainable' alternatives to resource-intensive construction systems due to their inherent recyclability, low embodied energy, minimal carbon emissions and excellent moisture and thermal regulation ability (Schroeder, 2015). In recent decades, earth construction has experienced renewed interest as a low-carbon 'natural building' technique with roots across global vernacular architecture.

Despite these advantages, contemporary applications of earth often rely on chemical stabilisation through the addition of cement or lime in order to meet mechanical, durability and regulatory requirements. While effective, these stabilisers significantly increase embodied carbon and compromise the recyclability of earth materials (Muguda & Wyndham, 2024), thus reproducing a linear material logic and undermining their sustainability.

In response, extensive research has explored alternative binders as stabilisation agents. These can be geopolymers, typically secondary materials derived from industrial waste streams such as fly ash, or naturally derived biopolymers, such as polysaccharides, proteins and lipids (Losini et al., 2021). While both effective in terms of mechanical performance, the latter stand out as frontrunners with regards to sustainability as they offer a bio-based solution with reduced carbon impact.

Natural biopolymer binders have a long vernacular history, with precedent for numerous animal and vegetable derived earth stabilisers – from manure to plant starches – appearing throughout history and global cultures (F. Konijnenberg, 2024). The majority of contemporary research, however, has been on industrially extracted biopolymers such as alginate, gums, lignin and crustacean shell derived chitin (Losini et al. 2021) (Sesay et al., 2025) . Recent studies indicate that it is possible to reuse/re-manufacture (Bruno et al., 2020) and recycle (Muguda & Wyndham, 2024) these biopolymer stabilised earth bricks at end of life – making this a fully circular alternative. However, notwithstanding their many positive attributes, many of these biopolymer admixtures remain primary raw materials extracted through chemical processes.

The investigation of possible secondary as well as bio-based materials for use as soil stabilisers remains, as yet, underexplored. EPS thus presents a compelling opportunity to expand the possibilities of sustainable earth stabilisation strategies.

Research Framework

The preceding introduction lays out the context, scientific and societal, in which this research is placed. This forms a general problem definition from which the following research framework is derived.

Problem Statement

In the context of the earth construction 'renaissance' there is a knowledge gap regarding low carbon, secondary and recyclable binders for earth-based materials.

Research Question

How can wastewater-derived extracellular polymeric substances (EPS) be employed as a bio-based stabiliser for earth construction?

Societal & Scientific Relevance

Scientifically, this research contributes to emerging knowledge at the intersection of waste derived bio-materials, earth construction, and architectural design. While extensive literature exists on bio-polymer stabilised earth, no research has yet investigated wastewater derived bio-polymers as stabilising agents. This project advances the understanding of EPS as a functional stabiliser and explores its compatibility with contemporary earth construction methodologies.

From a societal perspective, it responds directly to urgent challenges related to climate change, resource scarcity, and waste management. Rethinking sewage residues as construction resources introduces circular systems thinking to close material loops. By re-imagining sewage sludge - 'the waste of the waste' - as a valuable commodity, the project seeks to shift perceptions of problematic waste streams and contribute to broader efforts to transition towards a circular economy.

Research Objectives

The intended impacts and outcomes of this study are determined to be:

Demonstrate high value application for an abundant secondary resource – by incorporating a sewage sludge derived bio-polymer in a building product.

Reduce the impact of contemporary earth construction – by proposing a binder with lower emissions, no primary extractive resource impacts and better recyclability than cement, the industry standard.

Expand structural and formal applications of earth construction – by developing a bio-stabilised earth mix with competitive characteristics to analogous cement based alternatives.

Research Scope

This research focuses on the development and architectural application of EPS-stabilised earth at the scale of construction components. The scope includes material formulation and experimental testing. This is an exploratory study and, as such, does not aim to deliver full regulatory certification or industrial-scale implementation. It is instead positioned as foundational research intended to generate material knowledge, inform future applications, and contribute to discourse on circular, bio-based construction systems.

Experimental and Design Criteria

These will be defined through review of relevant literature in the subsequent chapters.

02.

Background

Details of Cork. Silkscreen print on steel with Kaumera, processed with flame, 40 x 60cm. Nesie Junyi Wang. 2024.

Extracellular Polymeric Substances (EPS)

Extracellular Polymeric Substances (EPS) are complex extracellular polymers secreted by microorganisms in the biological wastewater treatment process. These secreted polymers protect the microbes against harsh conditions, serve as a nutrient reserve and form a gel matrix that holds the sludge cells together (Huang et al., 2022; Hamed et al., 2025). They are macromolecules characterised by variable composition, which is highly dependent on numerous factors relating to: influent wastewater, microbial species, treatment process, environmental conditions and extraction methods (Hamed et al., 2025). The fraction of EPS known as alginate-like extracellular polymers (ALE), also more recently termed structural extra-cellular polymers (sEPS), will be the primary focus going forward as they present the most valuable properties and are most easy to source.

Extraction - Methods and Scale

Studies show that sEPS can be recovered from various biological wastewater treatment processes both traditional and emerging, namely: activated granular sludge (AGS), anaerobic digested sludge (ADS), conventional activated sludge (CAS), and algal–bacterial granular sludge (ABGS) (Cheng et al. 2024).

As of yet, there is no standardised extraction method for EPS, which remains a major barrier to industrial scaling. In a recent paper, Hamed et al. (2025) emphasise inconsistent research findings and call out the urgent need for methodological standardization. Conversely to broader EPS extraction, mainstream methods for sEPS extraction are limited to two (Cheng et al. 2024). Large scale extraction facilities for (s)EPS are already in operation at several Nereda wastewater treatment plants in the Netherlands – Zutphen and Epe – under the name Kaumera. It has been suggested that sEPS, being derived from such an abundant waste resource, could offer a cheaper alternative to the alginate market and reach a competitive production volume simply by installing extraction facilities at all existing Nereda wastewater treatment plants (TU Delft, Lucky find becomes top material. n.d.).

Due to their amphiphilic nature – displaying both hydrophobic and hydrophilic properties – (s)EPS possess diverse attributes applicable to a wide range of industries. Hydrophilic behaviour results in high water holding capacity which in turn plays a role in sludge dewatering and downstream handling logistics (Hamed et al., 2025). EPS are also highly adsorptive, which can result in the accumulation of a wide range of contaminants and therefore their removal from the primary effluents (ibid.). Extraction of Kaumera is reported to reduce overall sludge volume by 20- 35%, thus reducing the quantity destined for incineration and, consequently, the associated costs and GHG emissions (Haskoning. Kaumera, an innovation in resource recovery. n.d.). Cheng et al. (2024) compile several economic viability studies conducted for the Dutch market which estimate that by 2030 production could reach 85,000 tons annually, with a market value of € 170 million, a daily revenue for a single plant of € 36,000–730,000, and a reduction in sewage treatment operating costs of 50%.

Extraction of EPS at wastewater treatment plants is therefore positioned not only as a materials recovery strategy, but also as a process optimisation measure and business case for wastewater infrastructure.

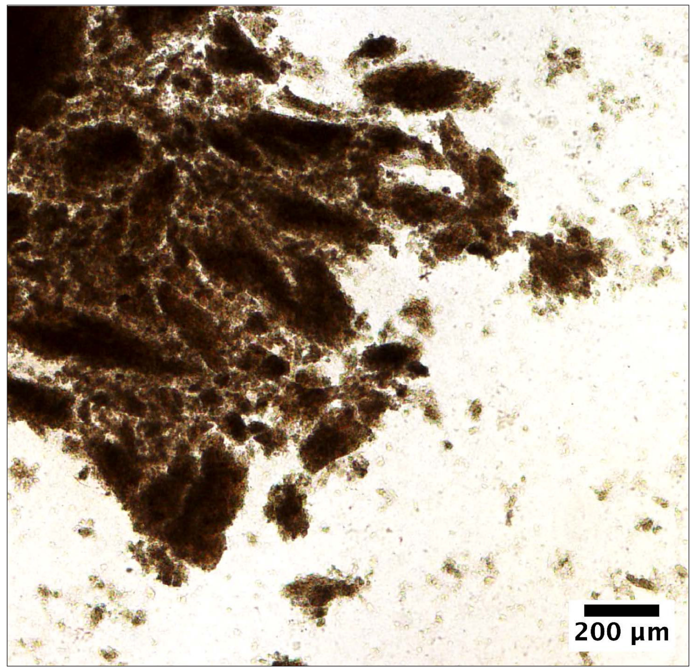


Figure 4. Optical microscopy image showing the coalescence of floccular gel like particles with "fuzzy" edges within EPS (Raja, 2025)

(s)EPS |	Structural Extra-cellular Polymeric Substances
Commercial Product	**Kaumera Gel**
Extraction Facilities	**Zutphen & Epe wastewater treatment plants** in the Netherlands
Organic Content	**~90%**
Biochemical Composition	**70-80%** **polysaccharides and proteins**
Water Interaction	**Amphiphilic** Both hydrophobic and hydrophilic properties
PH	**~2.5** Acidic

Table 1. Description and properties of (s)EPS

Properties

EPS composition is highly variable but consists primarily of polysaccharides and proteins, which make up approximately 70-80% of components (Hamed et al., 2025) [overview in Table 1.]. While these molecules are predominant, a considerable portion is also made up of proteins, humic acids, uronic acids, fulvic acids, nucleic acids and lipids (Duque et al., 2021; Huang et al., 2022; Hamed et al., 2025). ALE are so named because they also contain a high fraction of natural alginate structural blocks (Cheng et al., 2024). This biochemical composition gives EPS it's gel-like nature and underpins many of the functional properties.

EPS are considered biodegradable, with (s)EPS representing the fraction that is also soluble in water. These polymers display several unusual properties which are suitable for a number of applications - discussed subsequently and summarised in Table 2.

Applications in the Built Environment

Several of these properties are directly relevant to the built environment, although it should be noted that precedents remain scarce as this is a recently emerging field. The existence of sEPS was only confirmed in the 1990s and the first successful extractions were not until 2008, so all reported applications and exploratory product developments fall within the past two decades (Cheng et al., 2024).

Fire-proofing has been demonstrated using EPS as a coating for flax fabrics (Kim et al., 2019; Le et al., 2025) as well as in a master's thesis in which Dohmen (2025) applied unprocessed kaumera as a coating for timber panels to compare against other novel 'biobased' flame retardants. This is particularly relevant in the context of increasing fire safety requirements in the built environment, especially considering that, at present, the commercial flame retardant market comprises ~ 31% halogenated materials which are hazardous to human health (Duque et al., 2021). Waterproofing, which has so far been proposed in the context of industrial paper coating, would also be greatly beneficial in enhancing the durability of building products. Cement curing is the primary known application directly related to construction. While limited to a specific use case, it is well documented and indicates positive results with regards to the incorporation of sEPS in mineral material assemblies that use water – as is the case for earth building materials.

Conspicuously absent from these summaries are two additional properties which are considered relevant for this research. Binding, while a known property, is not extensively addressed in literature but suggests possible replacement of fossil-derived 'plastic' polymers in a range of products such as composites (Sauerwein et al., 2023). sEPS has been directly used as a glue or binder in several material studies and, in the built environment specifically, has been applied at pilot scale as a binder in a bio-composite branded Re-Plex (Sauerwein et al., 2023). This, as well as a novel waste-water derived calcite product, are further addressed in subsequent sections. Finally, the unpleasant odour of sewage derived (s)EPS is an aspect on which the literature does not extensively report. Nevertheless, this is highly relevant to investigating market applications and cannot be ignored as a significant issue.

Application	**Relevant Property**
(Waterproof) Coating Material*****	EPS display both hydrophilic and hydrophobic properties, with polysaccharides being film-forming and lipids being waterproof
Curing of cement*****	The hydrophilic properties of EPS improve curing of cement, reducing moisture loss from the surface of cement-based materials
Bioadsorbent	The phydiochemical interactions between the adsorbates of funcitonal groups of EPS promote the adsorption of metals or other compounds
Flame retardant*****	(s)EPS can be a bio-based flame retardant material for flax fabrics due to effective char formation. This property has been attributed to a high content of organic phosphorus (Hamed et al., 2025).
Bioflocculation	Some functional groups present in EPS contribute to flocculation abilities
Soil Conditioning	Water-binding capacity makes EPS applicable in the agronomic sector to retain water in soil and reduce leaching of fertilisers
Seed coating	Gel properties of ALE can isolate seeds from the external environment and serve as an organic carbon source

*Table 2. Applications of EPS in Different Industrial Sectors with built environment relevant properties labelled *. Combines tables reproduced from Duque et al., (2021) and Cheng et al., (2024) with AI generated icons.*

Barriers and Limitations

Cheng et al., (2024) summarise the current status of research on sEPS recovery and identify several key barriers and considerations.

Firstly, as a result of their highly variable composition, sEPS are non-standardised and the relative fluctuation of components makes it difficult to ensure a consistent product (ibid.). This complicates subsequent applications which are not be able to rely on reproducible functional properties. It may be less relevant, however, for applications which rely primarily on attributes related to the polysaccharide and protein content that makes up the vast majority of the molecular weight. These are essentially the properties which are considered relevant in this research.

Furthemore, while the recovery of sEPS generates a circular secondary resource, the process itself is not without environmental impact. sEPS extraction requires the use of numerous chemicals and energy intensive technologies (ibid.). In addition, the removal of a large proportion of the organic component of sewage sludge results in a less combustible material which must therefore be disposed of at greater energetic expense (Cheng et al., 2024). This is potentially countered by the reduced emissions profile of the eventual sludge incineration, which has a reduced volume and lower biomass content. Nevertheless, the overall environmental profile of these impacts represents a complex balance that is not yet well documented in scientific literature.

Finally, sEPS is generally considered to be nontoxic, however, it is understood that the adsorptive properties may result in the presence of contaminants. As has been studied for sewage sludge derived products, this comprises heavy metals, antibiotics, organic micropollutants, and others. Cheng et al. (2024) report that this is a consideration in need of further attention and underscore the urgency of understanding the environmental risks.

Figure 5. Container of Kaumera gel used for this project.

Kaumera Precedents

At present, Kaumera Nereda® Gum – extracted at Royal Haskoning's Epe at Zutphen wastewater treatment plants in the Netherlands – represents the only commercially available form of recovered EPS. As a result, all documented material and product application precedents use the Kaumera brand and are geographically concentrated in the Netherlands.

Several artistic projects were commissioned when Kaumera was first put on the market, these include: a Kaumera dyed Kimono by Studio Nienke Hoogvliet and a Kaumera based glaze by Billie Van Katwijk – both exhibited at Dutch Design week in 2018 (MaterialDistrict, 2019). The latter was later adapted as a collection of glazed wall tiles for the Exploded View Beyond Building exhibition by Biobased Creations (Studio Billie van Katwijk. (n.d.)).

There are only two examples of materials developed in the context of the built environment which use Kaumera as a component.

Figure 6. Images of comissioned Kaumera products made by artists for Dutch Design Week 2018. Clockwise from top left : Kaumera dyed Kimono by Studio Nienke Hoogvliet, Mudernism by Billie Van Katwijk and bio-binding by Jeroen Wand (MaterialDistrict, 2019).

Re-Plex

The first construction material application using Kaumera was a hot press moulded composite under the name Re-Plex. This was developed by the COMPRO research team (2020-2022), building on insights from an earlier initiative (WASCOM - Converting Wastewater into Composites), and brought together academic and industry partners from the AMS institute, TU Delft, BAM Infaconsult, NPSP, Chaincraft and TU Delft in a three year project (AMS. COMPRO: Creating a fully circular and bio-based building material from wastewater resources. n.d.). This research in turn follows from the development of the Kaumera method for EPS extraction at TU Delft (Wilfert et al, 2024) and the earlier development of the Nereda® granular sludge wastewater treatment technology under the WATER-MINING initiative together with Royal Haskoning. Product development using Re-Plex was explored by students of the MSc MADE Living Lab at AMS, who identified nature restoration in aquatic settings and façade cladding as possible applications. These formed the basis of several thesis and academic projects, tested in collaboration with a market party (Sauerwein et al., 2023).

Component	**Role**	**Amount** %
Kaumera	**Binder**	**33**
Recell (cellulose)	Fiber	25
Powder from plant source	Filler	5
Citric acid	Additive	27
Glycerol	Additive	8
Tap water	Additive	4

Material	**Tensile** MPa	**Modulus** GPa	**Strain** %
Re-plex	**7**	**2.7**	**0.3**
PHB+ Sawdust	21	3	-

Table 3.Component ratios and mechanical properties for Re-Plex. Reproduced from (Sauerwein et al., 2023)

The development of Re-Plex is presented by Sauerwein et al. (2023) in the PLATE conference proceedings as an example of Feedstock-Material-Product Combinations to approach renewable material development. All Re-Plex components are biobased, with both the fibers and binders originating from wastewater. The components are shown in Table 3.

Sauerwein et al. (2023) further summarise testing performed to determine the mechanical, durability and experiential qualities of the composite:

- Strength : three point bending test according to ISO 14125
- Fire resistance: flammability test exposure to naked flame for 12 mins
- Biodegradability: Sample immersion in fresh and salt water over seven weeks
- Experiential qualities: Ma2EK toolkit
- Weathering: field test exposing prototypes in several locations

The results produced insights at all levels – feedstock, material and product. The need for washing of the Kaumera gum was identified, with high salt concentrations hindering the material development. The mechanical properties are summarised in Table 3. – revealing low strength when compared to other bio-composites. On the other hand, positive results were observed during fire testing, with charring and minimal fumes or dripping.

In terms of biodegradability, the material kept its shape for the duration of the field test (seven weeks), with submerged samples initially increasing in weight before stabilising. Fungal and algal growth was present in the fresh and salt water samples respectively. The microbial activity was determined to indicate eventual biodegradability.

Field testing revealed that the material brittleness is a key issue, with samples of the nature restoration structure breaking during assembly and tiles restricted to flat panels because samples of 3D forms could not be released from the moulds. Samples also eroded significantly and released an unpleasant odour when wet.

Within the context of the COMPRO research project, several student theses were also published that investigated the sustainability, business case and feasibility Re-Plex. Among these, Heijdens (2021) conducted a Life Cycle Assessment (LCA) of Re-Plex which concluded that the material does not compare favourably to conventional alternatives such as Fire Retardant MDF. This is attributed to: the innovative production process which is much more energy intensive than the mature manufacturing process of commercial products, the short lifecycle of the product which is not very durable, and the use of critic acid as a cross-linking additive which, while biobased, is determined to have a significant negative impact on the overall performance. The author suggests replacement with a substitute chemical – Succinic acid – to perform the cross-linking function. This is a petrochemical derived alternative but, nevertheless, has a significantly lower footprint (Heijdens, 2021).

In summary, while the incorporation of Kaumera in this composite product demonstrates valuable material recovery of a major organic waste stream, the material formulation and fabrication is not well suited to the applications investigated. At present, the industry partners involved have dis-continued product development.

Buildmatterial

The second product developed using Kaumera is a commercial venture - Buildmatterial 0.8 by Omlab, a material innovation and design studio based in the Netherlands. This is an extrudable calcite-based mix, derived entirely from water treatment waste residues. It consists primarily of calcite recovered from drinking water purification and so positions itself as a 'cement-free' alternative to mineral based materials like concrete and ceramic. The project launched in 2021 and is executed in collaboration with TNO– a non-profit research organisation promoting innovation in the Netherlands – as part of the National Program for Emissionless Building (Omlab, 2024). Buildmatterial 0.8 is presented as a low-carbon, lightweight, biodegradable and recycleable product with the mechanical strength of C8 concrete (MaterialDistrict, 2022). The mix composition is given in Table 4.

Component	Source	Amount %
Calcium Carbonate	From water softening treatment by Aquaminerals	60
Cellulose	Screened during sewage treatment process	5
Kaumera and/or alginate	**Obtained during the Nereda sewage treatment process**	**5**
Water	-	30

Table 4. Ingredients and component ratios for Builmatterial, based on quantities given by Biobased Materials (2023)

Buildmatterial has not undergone detailed scientific analysis, so the specific properties contributed by Kaumera in this mix remain poorly understood. In informal discussion with Omlab they reported that the most notable effect of the Kaumera gel addition was improved drying and aesthetic appearance ie. fewer cracks, smoother surface. Nevertheless, a preliminary material datasheet developed in collaboration with TNO lists these characteristics (Omlab, 2024):

- MKI: 0.011 (concrete 0.0252)
- kgCO$_2$-eq: 0.14 (concrete 0.257)
- Density 1.5kg per liter (concrete 2.7)
- Strength class: C8 (comparable to gypsum concrete)

The material is showcased through a number of digitally manufactured 'proof of concept' 3D printed products intended to demonstrate the viability of high value products made from low value (waste) ingredients. A restroom cubicle with walls made from printed Buildmatterial blocks was displayed in a series of exhibitions: as part of the Dutch Design Week (2021), the Floriade World Expo (2022) and The Exploded View (2023) (Omlab, 2023). Other demonstrator products include a bat nesting box, slope reinforcement tiles and a stool (Omlab, n.d.).

Most recently, a TU Delft Master Thesis from 2025 uses Buildmatterial as the basis of an investigation of 3D printing roughness to design controlled acoustic properties of non-structural hollow blocks (Comendador C.E., 2025). The thesis was developed in collaboration with Omlab and exhibited at Dutch Design Week in 2025 but, importantly, uses a more recent variant of the Buildmatterial which does not include Kaumera (Comendador C.E., 2025).

Kaumera's gel form ultimately presents a challenge for Buildmatterial's further development. While Kaumera can be dried, this comes at significant energetic and financial cost, consequently Omlab is forgoing its inclusion in the latest Buildmatterial iteration. The product is now formulated as a dry powder for improved logistics and marketability – making it shelf stable and simplifying user experience to 'just add water'.

Re-Plex
Dry Kaumera
Binder

Buildmatterial 0.8
Gel Kaumera
Drying & appearance

Figure 7. Images of pilot-scale Kaumera construction products. Top: Re-Plex (Sauerwein et al., 2023). Bottom : Buildmatterial 0.8 (MaterialDistrict. 3D Printing With Waste Material From Water Treatment, 2021)

Building with Earth

Earthen construction is an ancient building method which has evolved from the earliest civilisations to the present day. Multi-storey structures dating back several hundred, and in some cases thousands, of years are extant across the world, from Peru to Yemen (CRAterre, 2022). The basic material composition of earth construction combines subsoil with water, coarse sand or aggregates, and occasionally stabilisers. Traditional construction techniques range from monolithic rammed earth (RE) and masonry systems such as adobe, to composite systems such as wattle and daub, in which earth in a plastic state is applied to a timber subframe (Houben & Guillaud, 1994). The main methods of working with earth, as defined by the International Centre for Earth Construction (CRAterre), are often represented in literature as a wheel [reproduced below] and categorised according to construction method or earth state (ibid.).

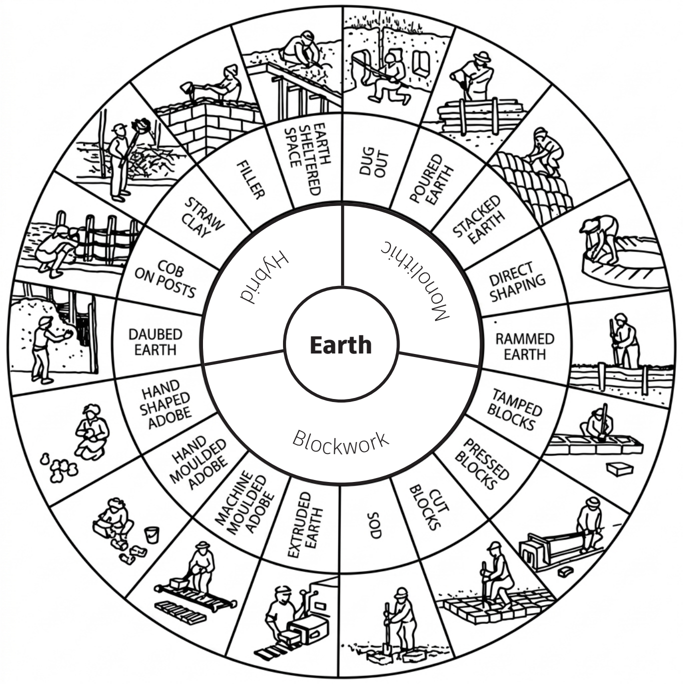


Figure 8. CRAterre's main methods and techniques of working with earth. Adapted from Houben and Guillaud (1994) with AI tools.

Earth construction is presently experiencing a contemporary "renaissance" as architects and designers reinterpret this historic material in response to growing environmental concerns. It's low embodied carbon, widespread local availability, and inherent circularity are leveraged across numerous recently completed architectural projects across the world. These many high-profile buildings illustrate a growing momentum. Of particular note is the work of Austrian rammed earth pioneer Martin Rauch and the Pritzker Prize-winning projects of Francis Kéré. Figure 9 showcases a collection of these projects.

Excavation Earth as a Secondary Resource

Contemporary approaches to earth construction have also integrated circular procurement strategies into this narrative. This shift is particularly significant given that the construction sector generates approximately half of all waste produced in Europe, of which excavation earth accounted for an estimated 75% in 2005 (Pelé-Peltier et al., 2022). Excavated site soil, previously regarded as a waste material requiring costly disposal in urban contexts, is therefore increasingly being reframed as a valuable construction resource.

A notable example is the Cycle Terre initiative in Greater Paris, which recovers excavated earth from major infrastructure projects, including the Paris Metro expansion, and transforms it into unfired earthen construction products (CRAterre, 2025). This circular approach extends to the Cycle Terre factory itself, which was constructed using earth blocks manufactured on-site alongside timber and reclaimed materials. Similar principles can be observed in projects such as L'Orangerie in Lyon, where approximately 500 tonnes of earth destined for landfill were sourced from excavation works 30 km from the construction site and incorporated into the building (Pelé-Peltier et al., 2022). These examples are included among the earth projects showcased overleaf.

Key Literature on Earth Construction

Foundational literature on earth construction often takes the form of practical "field guides", combining historical overviews of earthen architecture with technical guidance on material preparation, construction techniques, and both field and laboratory testing procedures. The principal texts reviewed in this research – alongside scientific and academic literature, particularly concerning the use of stabilising binders – are the revised edition of Building with Earth by Gernot Minke (2025) and Building with Earth: A Handbook by John Norton (1997).

Despite the growing prominence of earth construction, comprehensive standards and harmonised performance requirements remain limited. There is currently no direct equivalent in the Eurocodes specifically addressing earth, with the most advanced European regulatory frameworks being the German DIN and French NF standards. These define testing procedures and performance criteria for compressed earth blocks (CEB) only, rather than other earthen construction systems.

Characterising Earth Materials

The characterisation of earthen materials is complex but can be broadly organised into properties relating to mechanical, durability and environmental performance. These range from compressive and tensile strength to weathering resistance in the form of water or abrasion, to thermal and moisture regulation. Due to practical and programme constraints this research focuses on a single representative characteristic for evaluating technical properties in two of these umbrella categories – mechanical and durability performance. The chosen criteria were selected based on their relevance within existing literature.

Mechanical performance is assessed through compressive strength testing, as this is the most critical structural property and the only one addressed in the DIN and NF earth standards (DIN 18945)(NF XP 13-901). Minke (2025) notes that earth structures are traditionally designed to work almost exclusively in compression due to the material's negligible tensile strength. Other mechanical properties including bending strength, impact resistance, and corner durability are also discussed extensively in relation to handling and long term wear (ibid.) but were considered beyond the scope of the present study.

Durability assessment focuses on water resistance, which is widely regarded as the principal vulnerability of earth construction and appears as one of only three disadvantages in Minke's (2025) introduction to earth as a building material. Numerous water-related durability tests are described in the standards, including immersion, wetting–drying cycles, freeze–thaw resistance and capillary absorption (DIN 18945) (NF XP 13-901). Only stability in static water – in the form of immersion and submersion resistance – is investigated in this research, for reasons which will be discussed subsequently. Improved resistance to water is also a critical deciding factor determining the stabilisation of earthen materials with cement (Minke, 2025), as such, it provides a useful indicator of the effectiveness of EPS stabilisation against the industry standard.

Detailed descriptions of the associated testing methods and evaluation procedures are provided in the subsequent chapters.

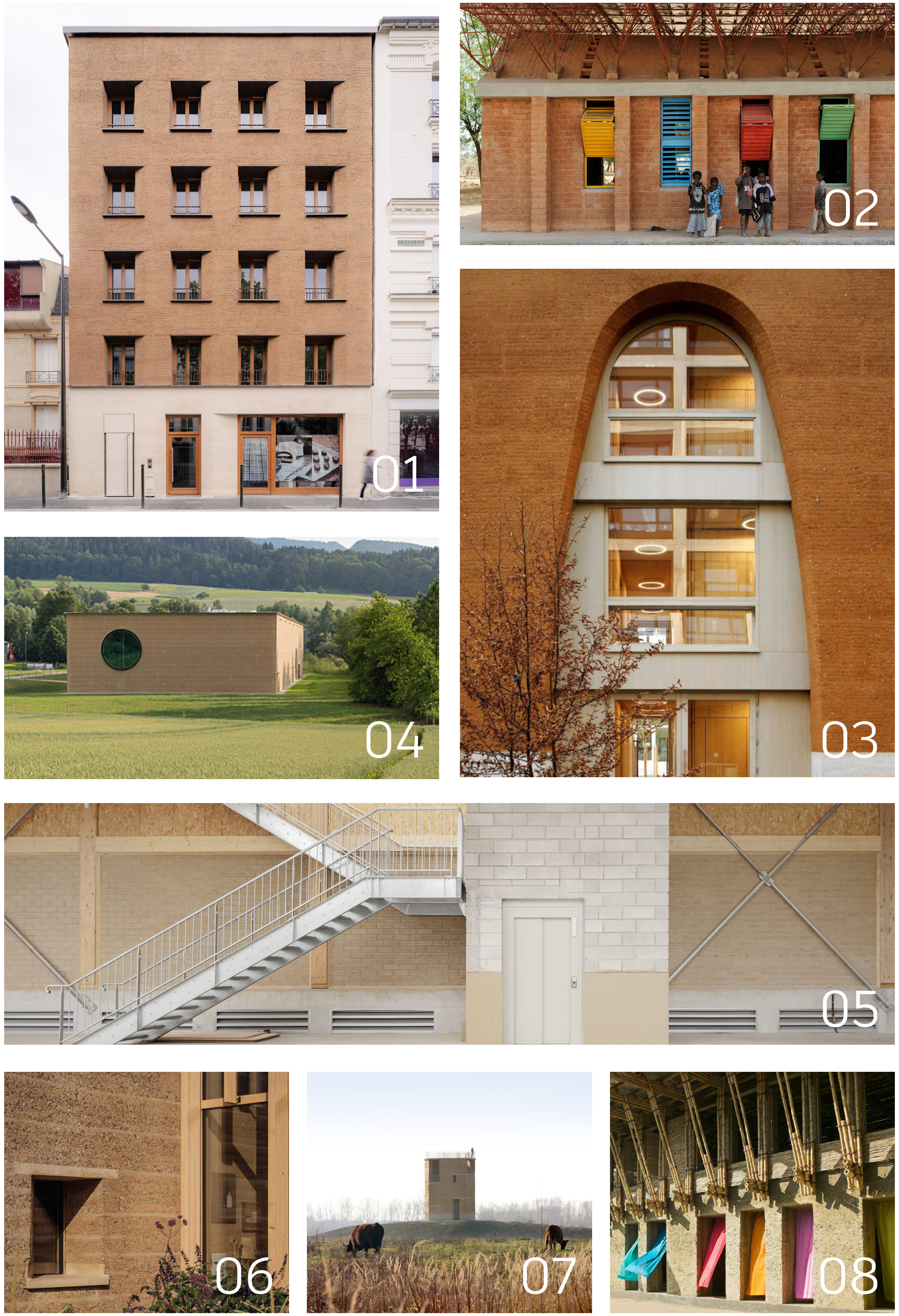


Figure 9. Examples of built projects using earth as a primary structural material. Projects:

01 | Quatre cheminees Residence
Déchelette Architecture, France, 2024

02 | Gando Primary school
Kéré Architecture, Burkina Faso, 2001

03 | Ricola Factory
Herzog & de Meuron, Switzerland, 2014

04 | L'Orangerie Offices
Vergely Architectes, France, 2021

05 | Cycle Terre Warehouse
Serge Joly, France, 2021

06 | Rammed Earth House
Tuckey Design Studio, United Kingdom, 2026

07 | Negenoord Observation Tower
De Gouden Liniaal Architecten, Belgium, 2016

08 | Meti School
Anna Herringer, Bangladesh, 2007

Bio-polymer Stabilised Earth

Despite the revival of earth building products as vernacular, low carbon construction materials, their inherent susceptibility to water-damage and erosion mean that contemporary construction practices typically require stabilisation in order to meet mechanical and durability standards. It is generally accepted that cement stabilised earth construction can have emissions equivalent to ceramics or concrete (Muguda & Wyndham, 2024). Minke (2025) relates that the addition of lime and cement in quantities below 5%, while effective for weather resistance, can detrimentally result in decreased compressive strength due to interference with the binding force of clay minerals, thus necessitating the addition of much higher additive content. The large thickness required for load-bearing earth elements such as walls, typically a minimum of 300mm, can therefore result in the paradoxical outcome that a cement stabilised rammed earth wall may contain more cement than a thinner, stronger, concrete wall in its place (Ma et al., 2024).

Thus, state of the art advancements in this field have increasingly proposed the adoption of bio-polymers derived from natural sources as a sustainable alternative to conventional cementitious and chemical binders.

Biopolymer Earth binders

A quick note on polymers: Polymers are large molecules made up of smaller repeating subunits (monomers) which can be categorised as synthetic or natural, many natural polymers are also biodegradable (Fatehi et al., 2021). All plastics, for example, are polymers, and the majority of these are derived from petroleum ie. fossil-based or synthetic. However, there are also many natural polymers that are produced by plants and living organisms – termed bio-polymers.

The long history of soil stabilisation using bio-polymers and other bio-based materials can be traced back to ancient techniques found across cultures and continents. These include: rice starch, eggs, animal gelatine, dung, ash, oils (linseed) and resins among others (Ma et al., 2024; Muguda & Wyndham, 2024; Konijnenberg, 2024; Turco et al., 2025). Modern research focussing on biobased soil stabilisation is therefore a successor to these historic building practices.

In the context of the climate crisis, contemporary bio-based alternatives offer a relatively lower carbon and renewable resource than industry standard cementitious and chemical binders. Beyond sustainability concerns, chemical stabilisers have also been shown to reduce moisture and thermal regulation performance and prevent recyclability (Losini et al., 2021). Biopolymers are preferable even to alternative secondary raw material binders, such as geopolymers obtained from industrial residues (eg. fly ash from solid fuel combustion), which also compromise the recyclability of earth based products at end of life (Muguda & Wyndham, 2024).

Losini et al. (2021) comprehensively review the latest investigations in natural additives and biopolymers used for earth stabilisation, collecting over 50 articles on the topic which are summarised in Table 5. The literature details experimental investigation of lignin, alginates, chitosan, guar and xantham gum (and others) applied to numerous earth building techniques..

Properties of Bio-stabilised Soils

The quantity of polymer added can vary widely, from below 0.1% in the case of some polysaccharide powders, to almost 20% in the case of alginate gels where this substitutes the addition of water (ibid.). Of particular interest to this research are precedents using alginate biopolymers, given the aforementioned similarities between these and sEPS. Similarities can also be drawn with gums, particularly Xantham gum, which similarly forms hydrogels displaying properties akin to alginates.

Bio-polymer	**Quantity** (wt%)	**Technique**
Polysaccharides & gelling biopolymers		
Chitosan	0.5-3	AD
Guar and Xantham gums	0.25-3	RE
Gellan and Agar gums	1-3	ST
Xantham gum	0.5-2.5	ST
Carrageenan	0.05-0.2	AD
Alginate	3-19.8	CEB, 3Dp
Proteins		
Casein	0.5-5	ST
Cow Blood	6.08	RE
Lipids		
Cooking oil	1	RE
Linseed oil	5	RE
Complex molecules		
Lignum	0.5	CEB
Tannins	1.14	CEB
Lignin	0-15	ST
Betroot & tomato	10	AD
Cow-dung	0-3	AD

AD = adobe | **CEB** = compressed earth blocks | **RE** = rammed earth | **ST** = soil stabilization

Table 5. Biopolymers classified into different categories, amended from Losini et al. (2021)

All of these polymers fall under the category of polysaccharides. Losini et als (2021) review covers recent studies investigating alginate biopolymers and highlights their use as fast setting binders for earthen 3D printing and in the preparation of compressed earth blocks (CEB) where high additive quantity takes the place of water. The latter CEB studies observed increased strength (both compressive and to an extent tensile) as well as increased water repellence and erosion resistance of the earth samples incorporating alginates in the soil mix or as a coating (ibid.).

Researchers have demonstrated that biopolymer stabilised soils, particularly using polysaccharides, exhibit comparable compressive strengths to cement-stabilised soils (Muguda & Wyndham, 2024). In the case of rammed earth (RE) specifically Sesay et al. (2025) review 45 precedents for bio-based stabilisation and draw the following conclusions: compressive strength is generally improved, tensile strength is generally low but the tensile-compressive ratios fall between acceptable limits, elastic modulus varies widely largely due to inconsistent measurement and calculation methodologies and biopolymers can increase water durability particularly in the case of lipid biopolymers with hydrophobic properties. The authors also highlight that issues with biodegradation are of particular concern, with mould growth in particular posing a significant disadvantage (ibid.). These are highly relevant findings for this research and will be revisited in the discussion of the results.

A final note on the positive attributes of bio-stabilisation is the possibility of recycling the bound soil, which is one of the major failings of cement and chemically stabilised earth. This has been showcased by several recent studies. Bruno et al. (2020) demonstrated that bio-stabilised earth bricks using guar gum could be crushed and remanufactured, retaining desirable compressive strength even after three cycles. Muguda & Wyndham (2024) fully 'recycled' stabilised soil samples through soil-washing – partially recovering the 'original' soil material separate to the binder, even after a second cycle of stabilisation and washing.

The ability of stabilised earth materials to be reused, reprocessed, or safely reintegrated into material cycles is considered a critical aspect of their long-term environmental viability. Sustainability (and circularity) assessment, in the form of recyclability, was therefore considered as an additional criteria to be investigated in this research.

Methodology

General Overview

The first phase of research involves laboratory-scale experimentation to develop and characterise EPS-stabilised earth mixtures. The aim is to establish the performance and determine optimal component ratios of earth formulations incorporating feasible ranges for stabiliser content. Results will be systematically compared against unstabilised soil mixtures, which serve as baseline references. In essence this project is an exploratory study which investigates material formulations not yet addressed in academic literature. As such, this phase is the most critical and is considered the primary focus of the work.

A high level secondary phase is dedicated to the development of possible product applications and a general discussion of the broader research outlook following this initial material characterisation.

A simplified flow-chart of the key project stages and chronological progression of the project is included below.

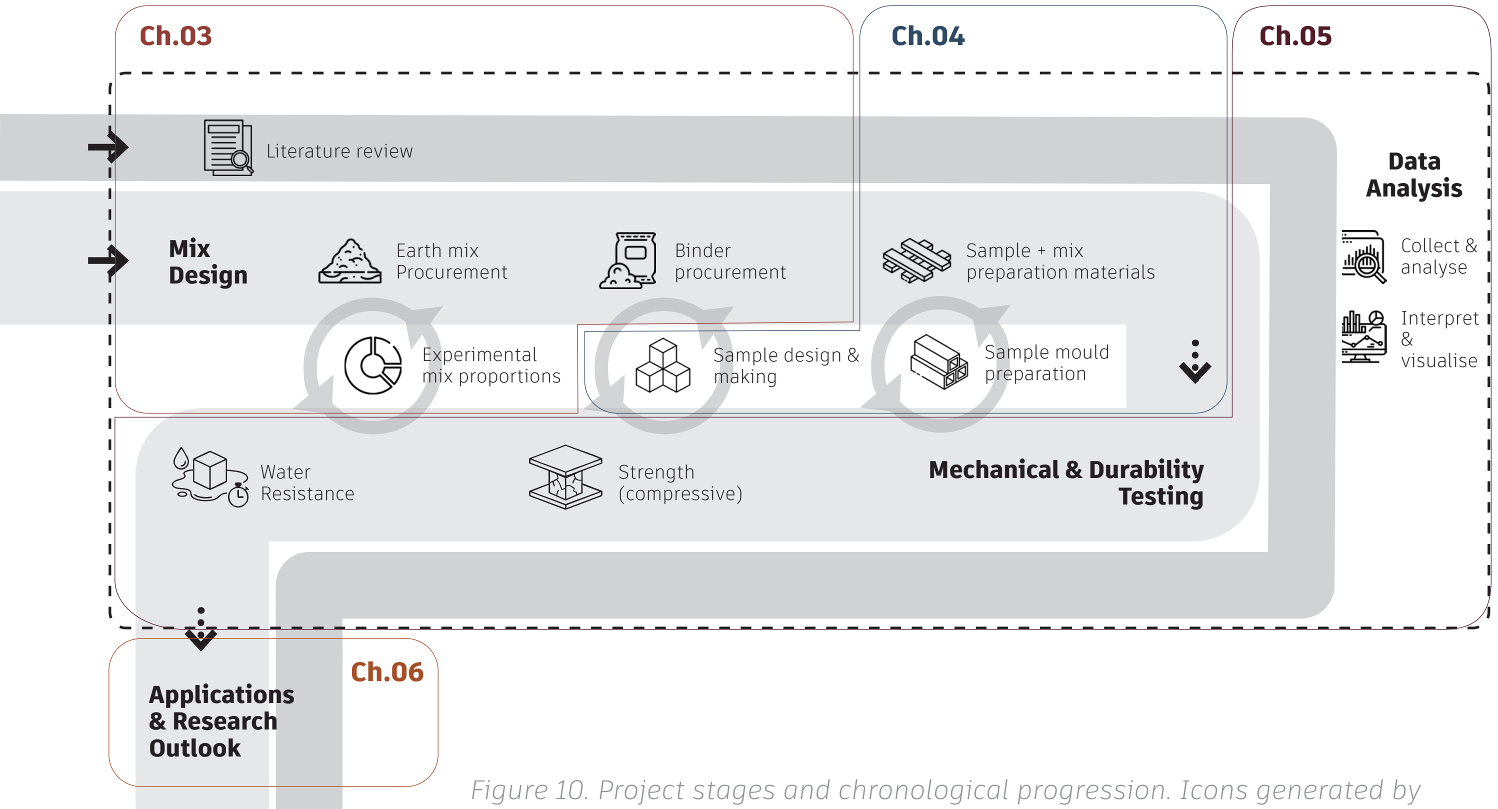


Figure 10. Project stages and chronological progression. Icons generated by Gemini AI or downloaded from Flaticon.com. Credits: Freepik, Soremba, iconfield, smashingstocks, monkik, ximrodx, Muhammad Atif

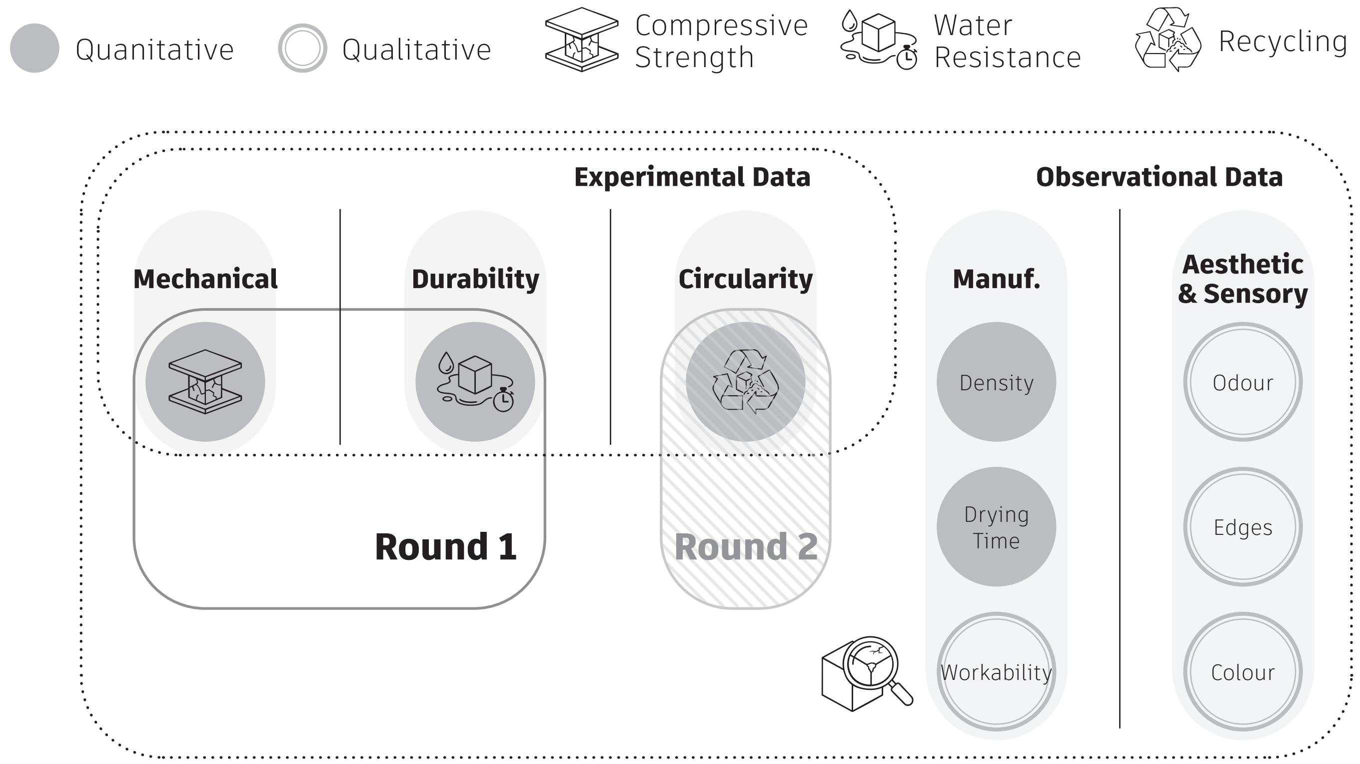


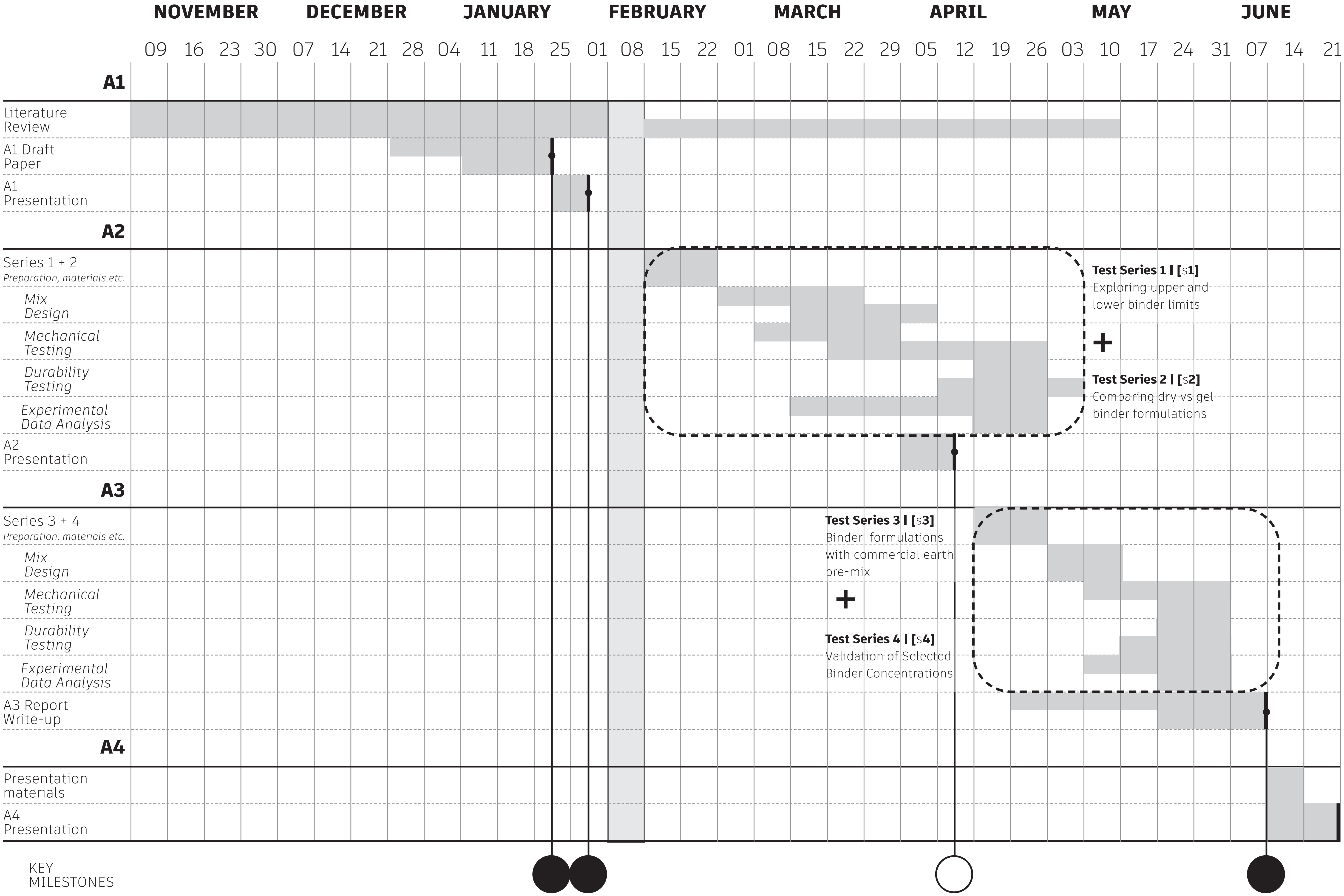
Figure 11. Key properties to be experimentally investigated. Icons generated with Gemini AI.

Key Criteria

Data collection combines both quantitative and qualitative measurements obtained through laboratory testing as well as direct observation. Characteristics to be investigated through experimental testing are derived from the preceding literature review and encompass key mechanical, durability, and environmental properties. The technical approach is shaped by practical constraints, including laboratory equipment and material availability. To ensure feasibility within the project timeframe, testing was prioritised into two phases. Due to material procurement and scheduling set-backs the second testing round could not be completed and exploration of the recyclability of EPS earth binders is therefore omitted.

Approaches to sample making and data collection are informed by the focused body of literature on earth construction previously discussed as well as standardised testing frameworks. In the absence of specific Dutch building standards for earth construction, this research draws on established norms from the German (DIN 18945) and French (NF XP P 13-901) standards. In addition, selected procedures from concrete testing standards, particularly the Dutch (NEN-EN 12390), are incorporated where relevant, given their high level of development and consistency. Together, these sources provide practical guidance on soil characterisation, mix design, and empirical testing methods applicable in both laboratory and field contexts. This methodological basis is used to define experimental protocols and the material mix design process.

Timeline



Test Series 1 | [s1]
Exploring upper and lower binder limits

+

Test Series 2 | [s2]
Comparing dry vs gel binder formulations

Test Series 3 | [s3]
Binder formulations with commercial earth pre-mix

+

Test Series 4 | [s4]
Validation of Selected Binder Concentrations

03.

Materials

Earth Mix Design

Earth

Earth construction uses natural soil which consists of clay, silt, sand and gravel. Literature on the topic typically refers to the base material as ‘loam’, describing a balanced soil with suitable particle size distribution for earth construction (Minke, 2025). The raw loam may be amended to achieve ideal composition, for example by adding a proportion of larger sand or gravel aggregates.

Soils are characterised according to particle diameter, with those smaller than 0.002 mm classed as clay, 0.002-0.06 mm classed as silt, 0.06-2 mm classed as sand and larger particles classed as gravel (ibid.). An appropriate soil composition for construction applications follows a graded particle size distribution which is essential to ensure adequate cohesion and compaction behaviour.

The maximum particle size is determined by the earth construction technique employed, with thick rammed earth [RE] walls requiring a range of particles sizes considerably larger than the range used for much smaller compressed earth blocks [CEB]. The ideal particle size distribution is commonly represented on a graph with the vertical axis displaying weight by percentage and the horizontal axis showing the particle diameter on a logarithmic scale (ibid.). In concrete mix design the optimal grading is described by Fuller’s parabola, whereas for earth construction achieving the ‘perfect’ distribution is less crucial. Generally, there should be sufficient sand to optimise porosity and strength while limiting shrinkage, and adequate clay content to achieve binding (ibid.).

In the case of CEB – the primary technique used in this research – Minke (2025) describes a leaner sandy loam as appropriate, with a maximum particle size of 4mm and a composition consisting of: 14% clay, 22% silt, 62% sand and 2% gravel [see Figure 10]. Norton (1997) gives a more generic recipe, suggesting that a suitable soil for earth block production should have 45-75% sand, 15-30% silt and 10-25% clay with a maximum grain size of 5mm.

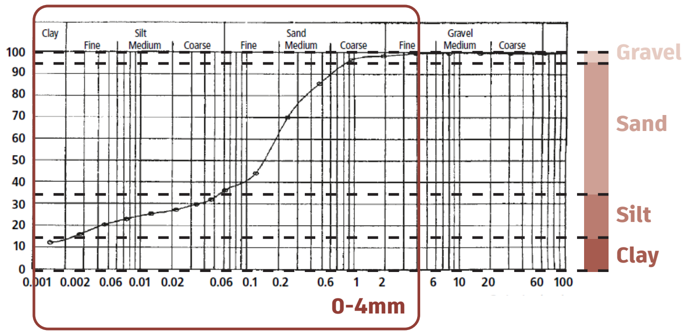


Figure 12. Soil grain size distribution appropriate for earth blocks, adapted from Minke (2025)

Several soil mixes combining different loams, aggregates and clays were investigated in this research. This included both commercially available engineered earth mixes for construction applications and mixes developed ‘in-house’ combining varying soil fractions. The best performing mixes, experimentally identified using simple tests, were subsequently used for sample preparation. These were generally found to be the engineered mixes from specialised suppliers. Due to extended lead-times it was not possible to procure sufficient construction grade pre-mix for the preparation of all experimental samples. The results presented therefore compare several different mixes. This can be considered advantageous in that the effects of the binder are tested against different clay minerals and particle size distributions – with varying degrees of success.

Water

The second ingredient needed to develop an earth construction material is water, with the optimal content again varying depending on the construction technique employed. This can range from 5-30% and is described as the amount at which maximum dry density is achieved when compacted (Norton 1997; Minke, 2025). The optimal water content can be established through a variety of tests with different degrees of complexity. This can range from the simple ‘Drop Test’ which requires no specialist equipment, to the Proctor test, which follows an international standard and is typically executed in a geotechnical laboratory. While this content represents maximum compaction, it is not the decisive parameter determining maximum strength. The strength of earth materials derives primarily from cohesion and binding force, for which it may be preferable to have a higher than optimal water percentage. Minke (2025) relates that the so-called optimal water content can effectively be considered a minimal water content, and that compressed blocks with a content 10% higher than optimal have been shown to demonstrate improved properties.

Establishing a Suitable Earth Mix

To define the correct composition and water content, the earth mixes investigated in this research were assessed using the drop test and then qualitative observation of their properties once formed into 80x80mm hand-rammed samples. These mixes are prepared using locally available materials which could be procured in the project timeframe - an overview is given in the form of a ‘procurement map’ below [Figure 13.]. The resulting optimal water content was then amended to a slightly higher content for the sample series. These initial mix development tests are summarised in the graphic on he following spread. As previously stated, the engineered earth mixes obtained from specialist suppliers, BC materials (via Cru Atelier) in Belgium and Oskam in the Netherlands, were identified as the most promising.

Figure 13. Procurement map of primary materials with logos of respective organisations. Unaffiliated and not endorsed.

DROP_TEST

A simple test to determine adequate binding force (optimal water content and grading) using visual cues, no specialised equipment required. This test is referenced in most primary texts on earth construction.

Test procedure adapted from Norton (1997) and Minke (2025).

Materials

Earth mix
BC | LB | OSK

Water

Equipment

Flat base container
Paint bucket

10-20 min

01

Prepare dry soil mix

02

Add water until you can form a ball with your hand but otherwise keeping as dry as possible

03

Form small ball which can fit comfortably in palm, approximately 40mm

04

Straighten arm at shoulder level and drop ball onto smooth clean floor (or flat based container placed on floor)

05

Observe breakage pattern:

- ✗ If ball remains intact and is only cracked or flattened it is too dry or has too high a clay content; add water or thin with sand and repeat test.
- ✗ If ball breaks into many small pieces it is too wet or to sandy; leave to dry and repeat test, if this breakage pattern persists the mix likely does not have sufficient binding force (clay) and cannot be used as a building material.
- ✓ If ball breaks into a few large pieces it is suitable for use.

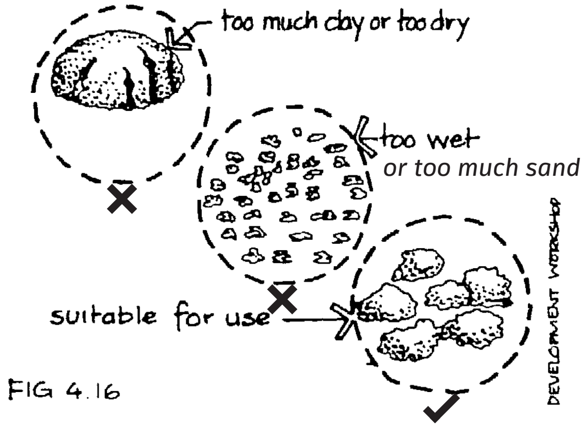


Figure 14. Drop test results. Figure reproduced from Norton (1997)

	BC	LB	OSK
Mix Proportion	100  BC		100  OSK
● **Aggregates** Sand+gravel 0-4mm		80  LB80_AM20 20	
Optimal Water %	**8-9%** 92:8	**8-9%** 92:8	**5%** 95:5
Drop Test	 ✓	 ✓	 ~
Hand-Rammed Sample			
Qualities	**BC** ✓ Clean edges ✓ Good compaction ✓ Uniform mix	**LB80_AM20** ✓ Clean edges ✓ Good compaction ✓ Uniform mix	**OSK** ✓ Clean edges ✓ Good compaction ✗ Sandy mix, slightly crumbly sample

Binder Concentrations

Unlike earth mix variations, the binder explored is limited to sEPS sourced from Kaumera's commercial extraction operations. The binding agent will be introduced in both solid [dry - KD] and liquid [gel - KG] form, and at varying concentrations relative to soil mass.

A table summarising the properties of the EPS batch used in this research was provided by Kaumera and is reproduced below:

Kaumera Batch **| KAUZPN2026001NB012**		
Concentration of solids (in gel)	**76.9**	g/L
pH	**2.4**	-
Preservative (Sodium Benzoate)	**0.12**	%
Volatile Solids (Organic Content)	**87.3**	%

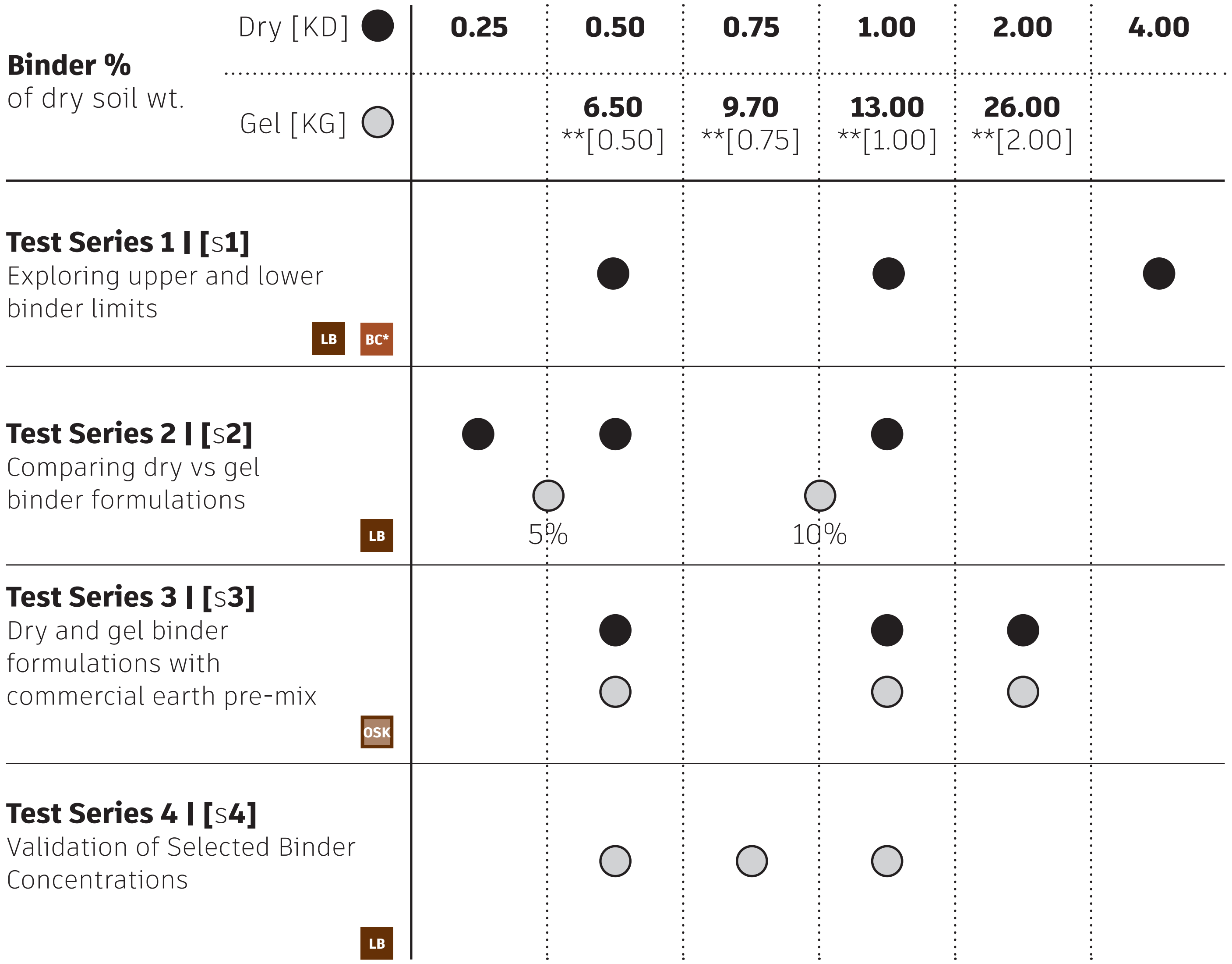
Table 6. Properties of Kaumera gel and dry powder used in this research (A. Raja, personal communication, 08 May 2026)

Based on bio-polymer stabilised earth research precedents, notably those compiled by Losini et al. (2021) and Sesay et al. (2025), optimal binder addition percentages typically range from around 0.05% to 3.00% of dry soil mass. This refers to dry binders in powder form, whereas in the case of liquid gels – for which there are only two studies reported in Losini (2021), using cow blood and alginate – the percentage can be as high as 20%. It should be noted that when comparing equivalent solids concentration, a hydrogel with ~10% solids (as is the case in this research) used at 10% dry earth weight would be equivalent to the addition of ~1% binder solids in dry format.

While the ultimate aim of the study was to utilise EPS in its gel form – the unprocessed product extracted from water treatment, and thus associated with lower emissions and embodied energy – the initial experimental programme focused on a dry binder series. This approach was intended to reduce variables, particularly by maintaining controlled water content, and to establish a preliminary understanding of optimal binder proportions before developing a corresponding gel-based series. Gel binder additions substitute the inclusion of water so that a consistent moisture content is maintained - ie. 5% KG additions have 5% less water - in line with approaches outlined in the studies discussed by Losini et al. (2021). On the basis of the precedents discussed, the binder percentages investigated were initially defined as 0.5%, 1.0%, 2.0% and 4.0% dry binder [KD].

The binder concentrations of successive experimental sample test series were amended throughout the project, in response to the data collected. It should be noted that the highest binder percentage considered for the gel addition is well above 10% and thus – the gel being composed of >90% water – represents a much higher water content than optimal for the investigated mixes. This also represents a different water content to the dry and lower gel content counterparts, making water content an uncontrolled variable.

The final binder concentrations used in successive test series are summarised in Table 6., noting that each series also includes a baseline with no binder (ie. 0.0%).



Binder % of dry soil wt.	0.25	0.50	0.75	1.00	2.00	4.00
Dry [KD] ●	**0.25**	**0.50**	**0.75**	**1.00**	**2.00**	**4.00**
Gel [KG] ○		**6.50** **[0.50]	**9.70** **[0.75]	**13.00** **[1.00]	**26.00** **[2.00]	
Test Series 1 | [s1] Exploring upper and lower binder limits (LB, BC*)		●		●		●
Test Series 2 | [s2] Comparing dry vs gel binder formulations (LB)	●	●		●		
	○ 5%		○ 10%			
Test Series 3 | [s3] Dry and gel binder formulations with commercial earth pre-mix (OSK)		●		●	●	
		○		○	○	
Test Series 4 | [s4] Validation of Selected Binder Concentrations (LB)		○	○	○		

* Only single samples made for each concentration test, full series not possible due to limited material quantity

** Dry solids equivalent, at 7.7% gel concentration

04.

Manufacturing

Sample Design

Samples for experimental testing were defined based on a combination of literature review, standardised testing norms, and practical manufacturing constraints.

Foundational earth construction texts, such as Minke (2026), provide guidance on mix preparation and both site and laboratory testing, but do not prescribe standardised methodologies for specimen production. In practice, sample preparation typically follows either established procedures for concrete testing (e.g. NEN-EN 12390) or specific standards for earthen materials, such as DIN 18945 and NF XP 13-901. Despite these frameworks, there remains significant inconsistency in sample design, particularly for compressive strength testing, which has been widely identified in literature as a major barrier to the comparability of results across studies. To compound the limitations listed above, sample dimensions in this research are determined not only by reference standards but also by the constraints of available laboratory equipment at TU Delft.

While the research initially aimed to investigate rammed earth, typically tested using cylindrical specimens with an aspect ratio of 2 or above (Pelé-Peltier et al., 2022), this method proved unsuitable for producing small-scale laboratory specimens. Following expert consultation, the alternative sample preparation technique chosen was Compressed Earth Blocks [CEBs], which allow for greater control, homogeneity, and reproducibility. Additionally, both the German DIN 18945 and French NF XP 13-901 earth testing standards are developed for this technique.

Sample Dimensions

The selection of a small cubic specimen was the result of iterative evaluation. Initial consideration was given to 150 mm cubes, in line with standard concrete testing practice and equipment calibration; however, this was impractical due to the large material volumes required, extended drying times, and incompatibility with available testing machinery. Rectangular, brick-like specimens were also considered, as these are the standard earth block format referenced in DIN 18945 and NF XP 13-901. Nevertheless, this geometry is not compatible with standard laboratory setups and many of the inconsistencies identified in literature result from the geometrical properties and necessary modifications required to adapt these rectangular blocks. High aspect ratios, characterised by large surface areas relative to height, can result in artificially increased measured strengths (Lan et al., 2021 ; Aubert et al. 2015). On the other hand, the cutting or stacking of blocks to achieve a more favourable aspect ratio (as described in the German and French standards) introduces additional stresses that can compromise strength (ibid.). While various correction methods have been proposed e.g. use of mortar capping, confinement plates, or empirical form factors, these have been generally been determined ineffective (ibid.) and no universally accepted standard exists. The use of cubic specimens mitigates some of these known issues.

Ultimately, 50 mm cubes were selected as the optimal solution: with minimised material use, lower drying time, compatibility with the available compression testing machinery and reliable production using a sheet press. Cubic rather than cylindrical samples are also advantageous in that they allow for greater evaluation of aesthetic properties like edge and corner definition, typically weak points in earth materials. This format additionally resembles the standard 40 mm small cubic specimen size used in the university concrete laboratory where testing was carried out.

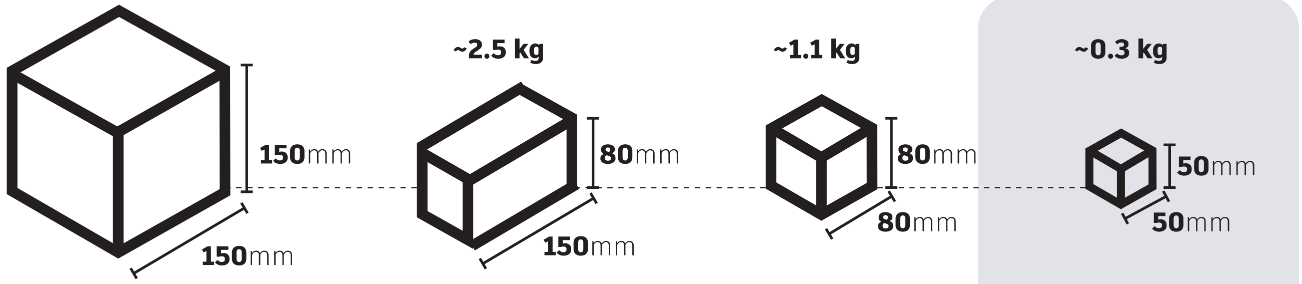
The quantity of material per sample is determined based on a target density of approximately 2500 kg/m^3, giving an earth weight of 313g per 50mm cubic sample. This is at the high end of the typical range defined by Minke (2025) and is over-estimated due to expected material loss or inconsistency during sample preparation.

Sample Making Technique

Samples were produced using a steel mould (50 x 50 mm hollow section) with a corresponding solid steel counter-mould, and compacted using 'The Green Village' 44 ton hydraulic sheet press. Applied pressure ranged between approximately 5-20 MPa, depending on the number of samples pressed simultaneously. This range is higher than typical pressures used in manual or commercial CEB production (generally 1-10 MPa) (Minke, 2025), but remains below the threshold associated with 'ultra-compressed earth blocks'. Variations in applied pressure across sample series are documented in Table7. and could not be standardised further as the machine pressure gauge measures in increments of 5bar.

	Samples no. pressed simult.	**Compaction Force** MPa per sample
[S1]	**1**	**20**
[S2]	**3**	**6.8**
[S3]	**5**	**7.1**
[S4]	**5**	**7.1**

Table 7. Compaction pressure for each consecutive test series



✓ Standard concrete test sample dimension	✓ Standard brick dimension	✓ Less material	✓ Least material, quick drying
✗ Too much material	✗ Numerous issues associated with testing	✓ Shorter drying time	✓ Can be made in press
✗ Long drying time	✗ Long drying time	✗ Cannot be made in press	✓ Fits in small testing machine
✗ Does not fit on small testing machine	✗ Incompatible with available testing machinery		

SAMPLE_PREPARATION

Materials

Earth mixture
BC | LB80_AM20 | OSK

Binder
KD | KG

Water

Equipment

Scales with high accuracy, able to detect mass below 2g

Mixing bowl

Mixing implement of suitable dimensions eg. Mixer egg-beater attachment

Large laboratory syringe with minimum 50ml capacity

PPE
Gloves | safety boots | safety glasses | masks | etc.

Portioning and filling equipment
Small containers | spoons

Custom moulds for 50mm cubic samples
Steel moulds [50x50x100mm] | solid counter-mould insert [50x50mm]

Steel base and top plates to cap moulds

Compression device with pressure or force gauge
Hydraulic sheet press

per batch

30-60 min

s1 + s2

01
Weigh out and mix together dry ingredients for all samples being pressed concurrently.

For [KD] samples, include binder

02
Measure water with syringe and gradually incorporate into dry earth using mixing implement until combined. **[≥5 mins]**

For [KG] samples, incorporate in place of or in addition to water

03
Mix by hand in order to homogenise mixture and achieve a finer texture

2 min

04
Portion out individual samples

s3 + s4

05
Place sample mixtures into hermetically sealed plastic bags

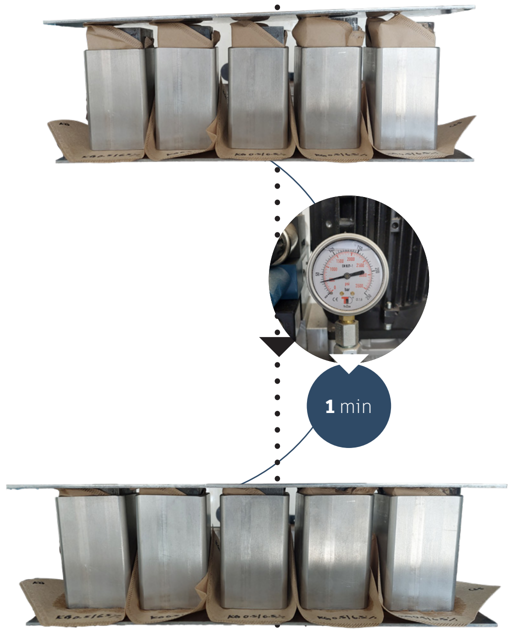
06
Leave mixture to 'cure' overnight or for at least 12h to ensure adequate clay hydration

12 hr

07
Prepare moulds with coffee filters at base to label samples and absorb excess water

08
Fill moulds with earth mixture

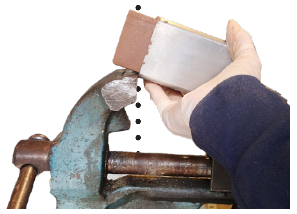
09
Transfer to hydraulic press, using steel base and top plates to protect in-built press plates.



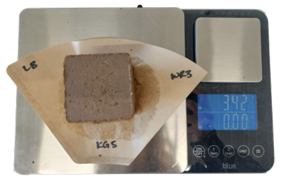
1 min

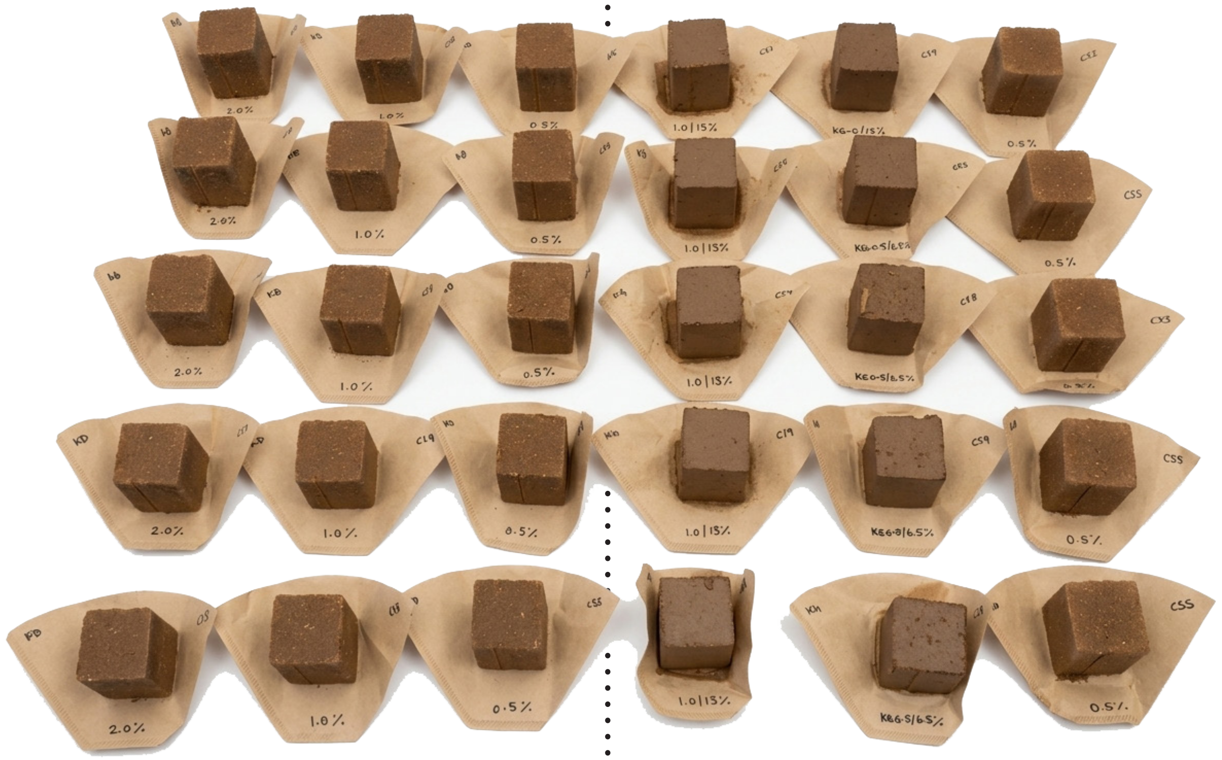
10
Compact at pre-defined pressure, holding for 1 min.

11
Carefully remove samples from moulds with table top vice to ensure minimal additional force



12
Weigh wet samples





13

Leave samples to dry indoors in a stable, ventilated environment

***Standardised to 7 days or oven dried where time constrained**

7 days*

14

Weigh daily until stabilised, with no mass change between consecutive 24h readings

NOTE *dry samples should reach given percentage of wet weight as water content is fixed ie. 90% for 10% water*

Boundary Conditions & Limitations

Several limitations in the sample preparation are acknowledged which may affect the accuracy and comparability of results.

Firstly, although the selected specimen size (50 mm cubes) was chosen for practical and methodological reasons, it does not align with the 40 mm cube standard typically used for small-scale concrete testing and so cannot make use of the custom inserts designed for the compression testing machinery. In addition, specimen geometry was not perfectly homogenous as variations in compaction depending on binder content resulted in slight differences in sample height and thus aspect ratio between specimens.

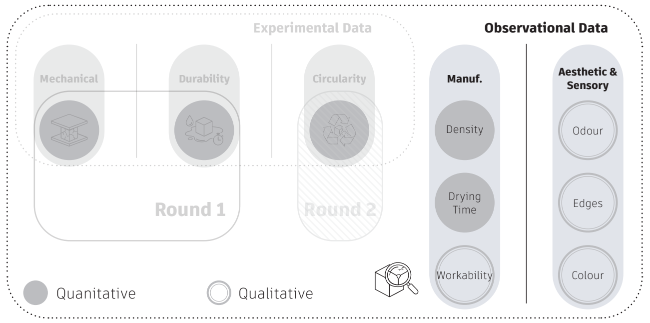
The demoulding process also introduced potential inconsistencies. Samples were manually extruded from the mould, and in some cases experienced minor drops or impacts while still wet, which may have introduced localised surface deformation or affected internal structure.

Control over the applied compaction pressure was also subject to human error. The hydraulic pressure gauge was read visually during operation and tended to fluctuate or 'jump' rather than increase smoothly, making it difficult to stop compaction precisely at the intended target pressure. As a result, some specimens were likely compacted slightly above or below the desired pressure level. For test series in which five samples were pressed simultaneously, a slight bowing of the steel capping plate may also have resulted in uneven pressure distribution and non-uniform compaction between specimens.

Finally, variability and internal imperfections may have arisen from the granular composition of the soil mixture, which, although specified as having a maximum particle size below 4 mm contained occasional particles which were visibly larger. These may have contributed to poor grading and localised voids within certain specimens.

These limitations are inherent to the exploratory nature of this study and the field conditions of the experimental process. As such, they should be considered when interpreting the results.

Observed Properties



Quantitative observations included density, and drying time, while qualitative observations focused on workability, odour, colour, and the sharpness of edges and corners after demoulding. These forms of assessment are typical when working with earth in field conditions. Quantitative characteristics such as density are commonly used as indicators of compaction quality, grading, and expected compressive strength, while drying time provides an indication of clay content and overall mix suitability (Minke, 2025 ; Norton, 1997). Qualitative observations are also well established within earth construction literature; with both Minke (2025) and Norton (1997) describing sensory evaluation methods, including visual inspection, touch, smell, and even taste, as part of understanding and characterising loam-based materials.

Qualitative observations were considered equally important in this research, with odour emerging as a significant factor due to the origin of the binder material. EPS, derived from wastewater treatment processes and composed primarily of organic matter, has a strong malodour in both dry and gel formulations. Despite frequently arising in informal discussions with researchers, artists, and designers who had practical experience working with the material, this characteristic remains largely absent from the reviewed academic literature and published material precedents.

These observed properties proved particularly valuable during the early test series, in which a broad range of binder concentrations was explored to establish feasible dosage ranges. Notes relating to workability, visual appearance, and odour were crucial in identifying promising formulations for subsequent testing phases. In later series, data collection was reduced to essential characteristics such as density, workability, and odour. Other attributes, including drying time, were standardised based on earlier findings.

QUANTITATIVE_DATA

Materials

Prepared sample series
50mm cubes

Equipment

Scales with high accuracy, able to detect mass below 2g

Measurement device
Ruler | Calipers

Marker pen

01
Prepare sample series as per methodology described

02
Collect quantitative sample data.
Weight, dimensions (lengthx2, widthx2, heightx2)

03
Continue to weigh samples daily (when possible) to collect data on drying time

04
Once complete drying ensured, label samples according to binder type, content and intended testing application

Naming Convention
[Binder+Type][Content%]_[IntendedTest][Sample No.]
Example
[Kaumera+Dry][0.5%]_[CompressiveStrength][1]
= KD0.5_CS1

05
Collect quantitative sample data.
Weight, dimensions (lengthx2, widthx2, heightx2)

06
Where necessary calculate properties eg. density

QUALITATIVE _DATA

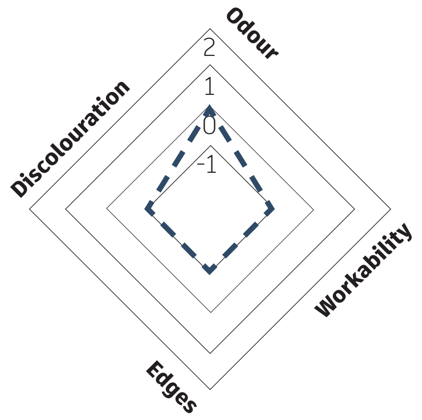
Qualitative Data was documented through photographs and laboratory notes, recording relative improvement or deterioration compared to an unstabilised baseline sample. These observations are summarised graphically in the results section using comparative visual scales indicating relative performance. The category descriptions for each property are based on early observations.

Materials

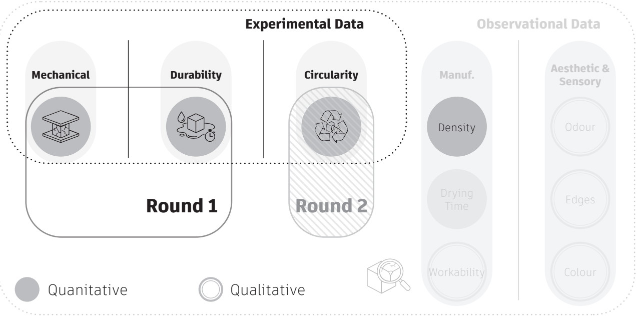
Prepared sample series
50mm cubes

Odour	- -	0 Neutral	1 Unpleasant	2 Malodorous
Colour	-1 Smooth	0 Neutral	1 Speckled	2 Streaky
Workability	-1 Fine-grain	0 Neutral	1 Tacky	2 Paste
Edges	-1 Sharp	0 Neutral	1 Rough	2 Crumbly

Target



Experimentally Derived Properties



Mechanical - Compressive Strength

The objective of the compressive strength testing was to evaluate whether EPS-stabilised earth mixtures exhibited improved performance against an unstabilised baseline and to identify differences in mechanical behaviour. As such, related parameters including density, failure mode, and sample consistency were recorded in addition to ultimate compressive strength.

As discussed in the section on sample preparation, compressive testing methodologies for earthen materials remain highly inconsistent and are strongly influenced by specimen geometry (Aubert et al. 2015 ; Lan et al., 2021). Existing literature identifies aspect ratio and surface treatment as key variables affecting measured strength (ibid.). While numerous approaches have been proposed to address this issue, including the use of correction factors and Teflon capping, previous studies have shown these approaches to yield limited success as results continue to demonstrate high variability (ibid.).

Considering no universally accepted testing procedure currently exists, a hybrid testing approach was developed for this research. Purpose-made cubic specimens were tested using a procedure adapted from concrete testing standards (NEN-EN 12390), while maintaining preparation methods suitable for earth materials. Earth testing standards (DIN 18945 ; NF XP 13-901) specify a minimum of six compression test samples per series. This was not possible given material limitations, nevertheless, a minimum of three specimens was tested to provide basic validation.

Target performance ranges are informed by classifications and minimum requirements described in the German DIN 18945 and French NF XP 13-901 standards for compressed earth blocks. Experimental results are compared against these strength class categories, given in table 8.

Durability - Water Resistance

Earth construction materials are particularly susceptible to weathering through abrasion and moisture exposure, with water generally considered the most critical degradation factor. There are, therefore, numerous testing procedures identified in literature and within earth construction standards relating to water damage. These include spray erosion tests, wetting–drying cycles, capillary absorption, freeze–thaw resistance, and immersion testing (DIN 18945 ; NF XP 13-901). Both the German and French standards incorporate all of the listed procedures.

Among the methods outlined, immersion testing was selected for this research due to its relative simplicity and suitability for field-scale conditions. This form of testing provides a direct indication of the material's resistance to severe water exposure and allows clear visual comparison between stabilised and un-stabilised specimens.

While authors such as Minke argue that immersion testing is of limited practical relevance, as earthen structures should always be protected from standing water through detailing strategies (plinths, roof overhangs etc.), the test remains valuable as an indicator of extreme conditions. Ouedraogo et al. (2020) propose that immersion resistance can be understood as a proxy for the "ultimate limit state" of earthen construction in the context of increased flooding and extreme weather events associated with climate change.

This research uses a combination of two water resistance tests, the immersion (or 'dip') test to obtain quantitative results and the full submersion (or stability in static water) test to visually assess sample deterioration under prolonged exposure.

The target mass loss categories for immersion testing defined in the DIN and NF standards are presented in Table 8., together with the corresponding minimum classes for stability under static water exposure. It should be noted that the data collected in this research is not directly comparable to these target immersion classes, as the testing procedure used here was adapted from the standard methods. However, the standards themselves express mass change as a percentage loss, despite the immersed surface area being determined by a fixed immersion depth of 10 cm rather than by specimen dimensions. Given that full-size rectangular CEBs typically range from approximately 20–40 cm in height (DIN 18945 ; NF XP 13-901), the adjusted immersion depth of 2 cm used for the 50 mm specimens in this study is considered proportionally comparable and is therefore assumed to yield results that can be evaluated against the standard target classes.

Compressive Strength

	Class	DIN	NF
		Mean Strength MPa or N/mm^2	
	0	-	<1.0
	1	-	>1.0
*	**2**	2.5	**>2.0**
	3	3.8	>3.0
	4	5.0	>4.0
	5	6.3	>5.0
	6	7.5	>6.0

Water Resistance

	Class	DIN	NF
		Mass Loss in Immersion Test **%**	
	-	-	-
**	**1**	<5	**<5**
	2	<20	<5
	3	-	-
	4	-	-
	-	-	-
	-	-	-
		Submersion time to disintegration **min**	
**	-	**45**	**120**

Targets	
*2	Minimum strength class for load bearing masonry
**1	Application class for external, exposed walls without plastering
-	Resistance to disintegration under static water is not directly stated in the standards consulted, but is referenced in both Minke (2025) and Ouedraogo et al. (2020) as appearing in other DIN and NF standards.

Table 8. Target performance ranges for compressive strength and water resistance. Adapted from (DIN 18945 ; NF XP 13-901)

COMPRESSIVE_STRENTH_TEST

Laboratory scale experimentation to determine compressive strength of tested samples. This methodology combines elements from NEN, DIN and NF standards, although is primarily derived from the former as earth specific standards pertain to rectangular geometries. The compressive testing procedure (after sample preparation) is fairly consistent across all the standards.

Materials

Prepared sample series
50mm cubes

Equipment

Compression testing equipment
Macben compression machine

per sample

5-10 min

01

Prepare, dry and label sample series, ensuring that measurements have been taken of testing surface, weight and density

At least three samples needed for each binder content to ensure data validation

02

Place sample in testing machine, at center of base plate, and ensure minimal distance between plates and sample

This can be adjusted using additional stacked steel base plates, although as 50mm is a non-standard dimension a gap always remains.

03

Cap sample on both sides with six stacked post-its (paper) to ensure smooth testing surface and minimal gaps between sample and plates

s3 + s4

04

Run machine test in the ‘cube compression’ setting with following parameters:

Rate	0.1 KN/s	
Start Load	0.5 KN	s1 + s2
	0.1 KN	s3 + s4
Stop load	40 %	

05

Remove samples from machine after failure, store in labelled plastic bags for recycling

CS samples were intended for recycling but this was ultimately cancelled due to scheduling

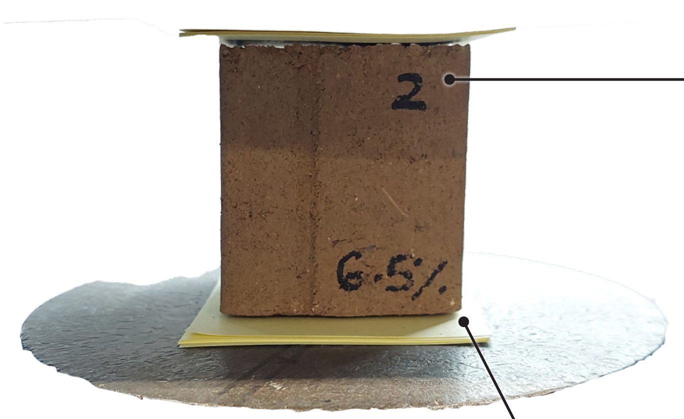
06

Clean machine plates to ensure no additional friction introduced from surface residue

07

Save and download data to USB before testing following sample

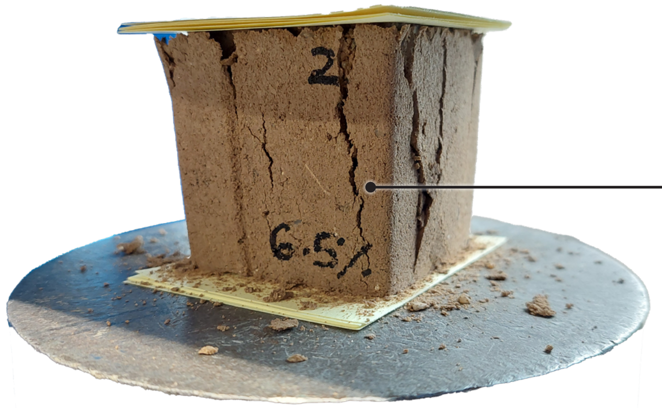
Preparation



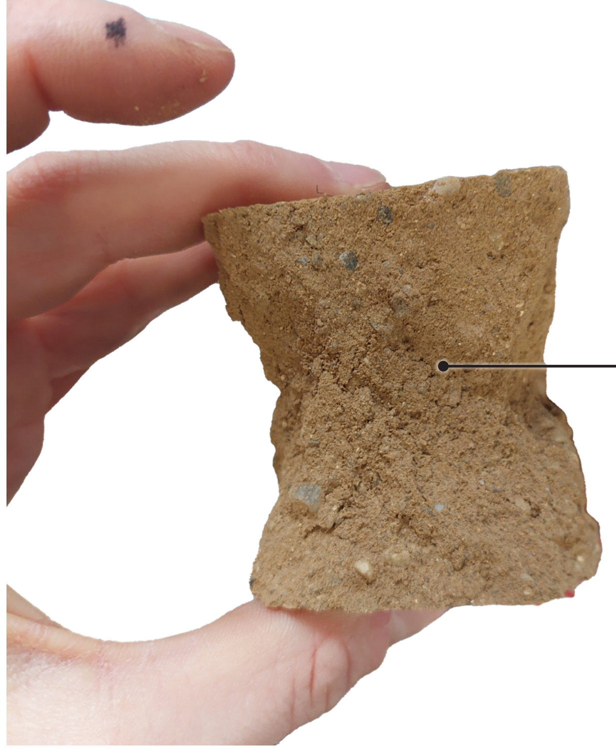
01
Sample label

03
Paper capping

Failure



Tested sample



Failed Sample
Displaying typical cube failure pattern for well graded brittle materials

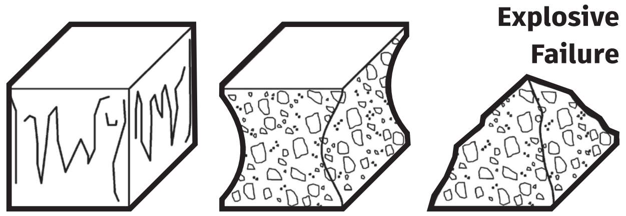


Figure 15. Satisfactory failures of cube specimens, adapted from NEN-EN 12390-3(2019)

All four exposed faces are cracked approximately equally, generally with little damage to faces in contact with the platens. (NEN-EN 12390-3, 2019)

IMMERSION_TEST

This procedure is adapted from the immersion testing methods defined in the DIN and NF standards for compressed earth blocks. In the standards, a full-size brick specimen is immersed to a depth of 100 mm for 10 minutes, after which mass loss is assessed. At only 50 mm in height the samples produced in this research are not compatible with the standardised setup. An amended testing approach was therefore developed maintaining the same general principles.

Materials

Prepared sample series
50mm cubes

Demineralised water
Approx 500ml per sample

Equipment

Scales with high accuracy, able to detect mass below 2g

Small plastic box with minimum 50mm height and 10mm width

Clamps suitable for resting on box edges
Small | lightweight | streamlined

Per sample

15 min

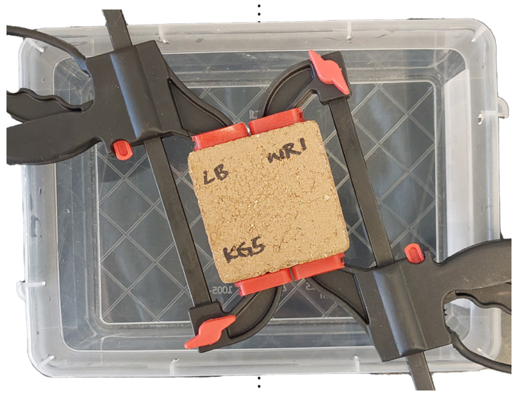
01

Weigh dried samples

02

Measure and mark a line along sample faces at 20mm from base (not labelled)

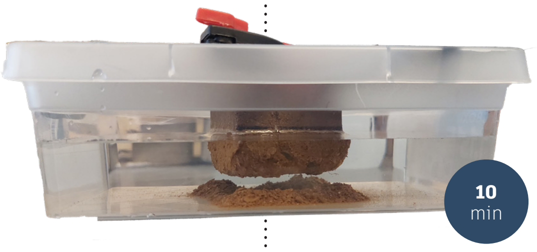
This is assumed to be just under half



03

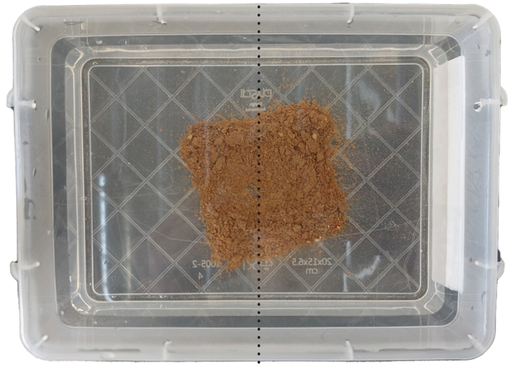
Suspend sample in water tight box and fill with demineralised water up to marked line (ie. 20mm immersion depth)

Using clamps resting on box edges



04

Keep suspended and immersed for 10 mins



05

Remove sample from water and leave to dry with labelled (top) face down until no mass change between consecutive 24hr readings

Standardised to 7 days or oven dried at 60C where time constrained

06

Repeat procedure for all samples to be tested in series

07

Weigh dried samples and calculate mass loss compared to pre-immersion weight

SUBMERSION_TEST

Adapted from Norton (1997) and academic references such as Ouedraogo et al. (2020). For series 3 and 4, this utilised the same samples that had previously been immersion tested as it was not possible to prepare an additional set solely for submersion. Both water resistance experiments were therefore performed on the same set.

Materials

Dried sample series previously immersion tested
50mm cubes

Demineralised water
Approx. 3l per series

Equipment

Large waterproof container in which all samples can be placed

Timer

Picture taking apparatus

Per series

120 min

01

Place samples in waterproof container arranged according to binder content, leaving adequate spacing between them

Where using previously immersion tested samples, place eroded face downwards so labelled faces are visible

s**3** + s**4**

02

Fill container with water until all samples are fully submerged, making sure to hit the container directly rather than pouring onto the samples

03

Visually document deterioration with images at pre-determined time stamps:

T0	5 min
T1	10 min
T2	15 min
T3	30 min
T4	45 min
T5	60 min
T6	90 min
T7	120 min

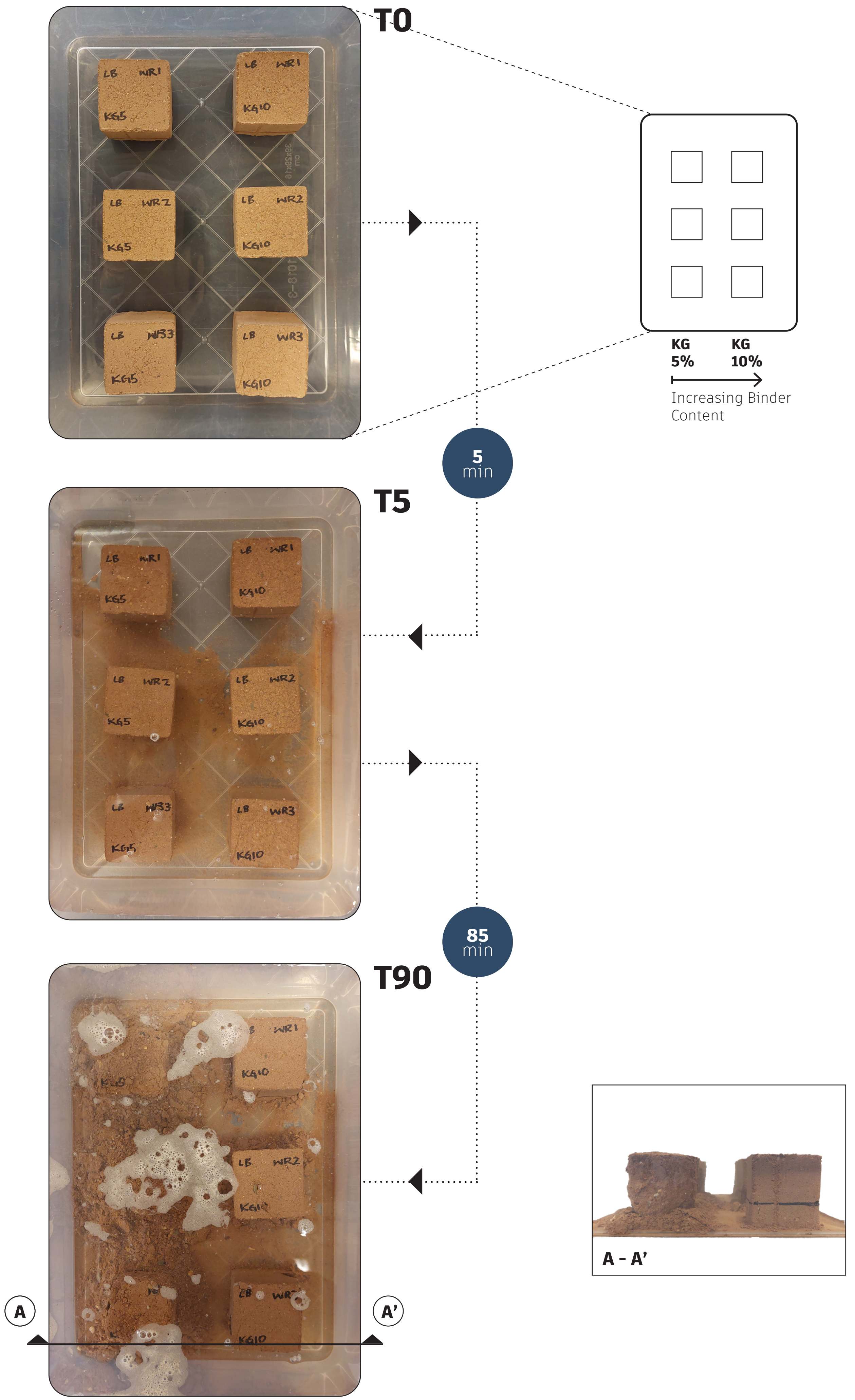
04

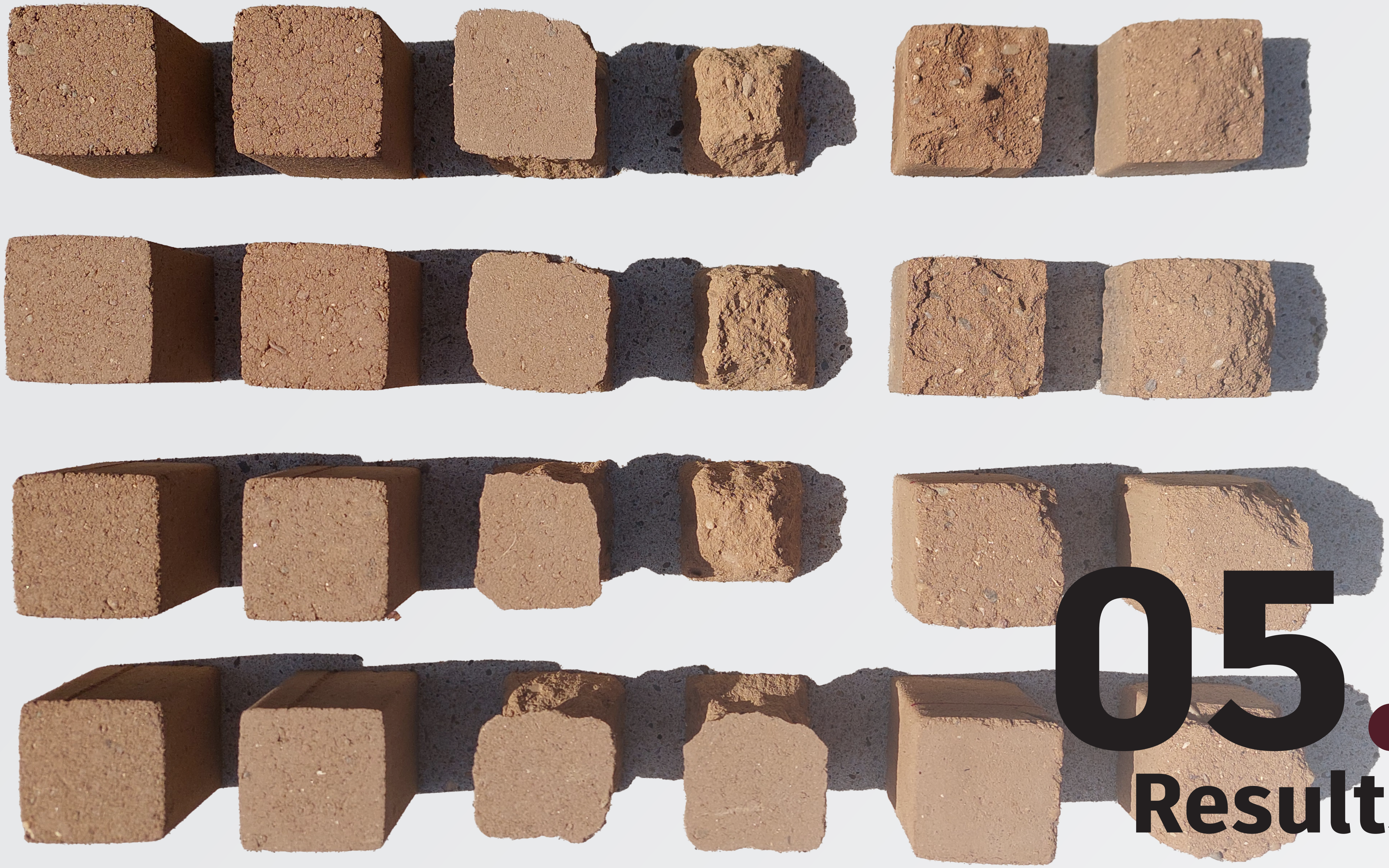
Make note of time to significant damage and to complete disintegration for each sample

NOTE surface deterioration to the point that the label is illegible constitutes significant damage, even if the sample still appears intact ie. cubic

05

Any samples which have not yet disintegrated after 120min should be removed and left to dry





05.

Results

Series 1

[S1]

Exploring upper and lower binder limits

Earth Mix	LB	BC

Binder % of dry soil wt.	● 0.25	0.50	0.75	1.00	2.00	4.00
Dry [KD] ●		●		●		●
Gel [KG] ○		6.50 **[0.50]	9.70 **[0.75]	13.00 **[1.00]	26.00 **[2.00]	

Sample Compaction MPa	20
No. Samples of each concentration	1

** Dry solids equivalent, at 7.7% gel concentration

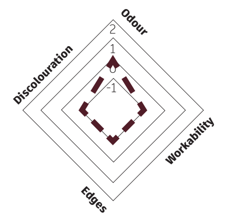
This series tested only individual samples for each binder concentration and was intended as a preliminary study to gauge whether the proposed concentration ranges were suitable, as such, emphasis is primarily placed on the maximum and minimum concentrations - 0.5, 1.0 and 4.0%. Only dried Kaumera was investigated as this allowed for greater control of variables.

Observed Properties

The highest binder concentration (4.0%) was found to be excessive, producing samples that were visibly discoloured, strongly malodorous, and unable to compact consistently to the desired target dimensions. In addition to performing poorly in the initial qualitative evaluation, one of the crushed [CS] 4% binder samples grew mould after several weeks of storage in a sealed plastic bag. It is assumed, given the high organic content in the binder, that this was due to trapped moisture. Mould was observed on only one high binder concentration [4%] sample, suggesting that there is a maximum allowable content beyond which earth and EPS formulations are susceptible to fungal growth.

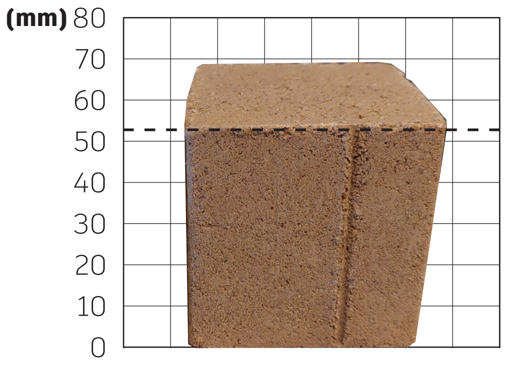
In contrast, the lowest investigated concentration [0.5%] remained visually comparable to the unstabilised baseline, exhibiting only minor spotting or speckling and a faint odour that became almost imperceptible after drying.

The following graphics showcase the stark visual contrast between these two extremes for samples made with the LB mix.



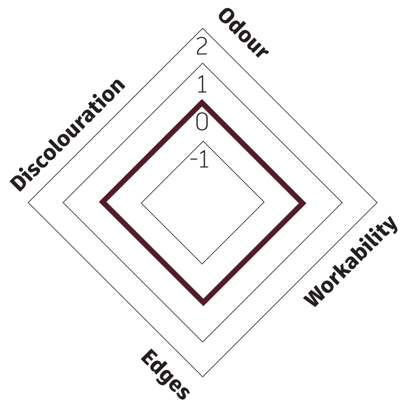
Target

0.0%

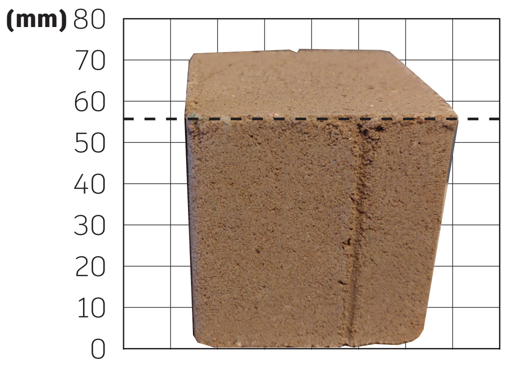


Density
~2270 kg/m3

Drying time
~2 days

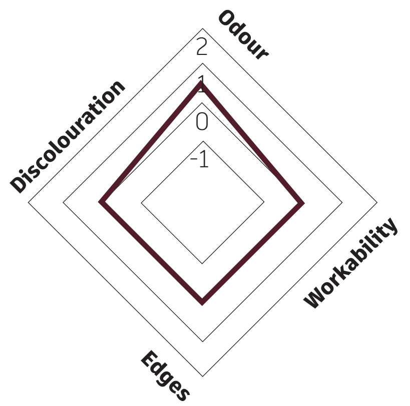


0.5% KD

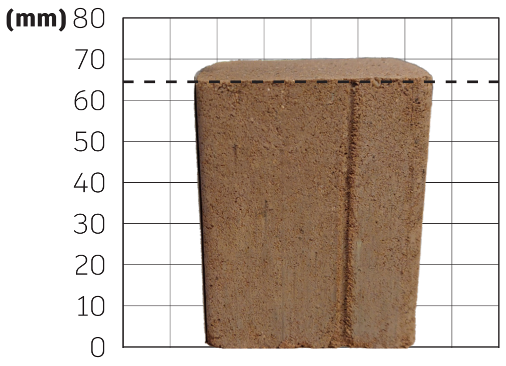


Density
~2031 kg/m3

Drying time
~2 days

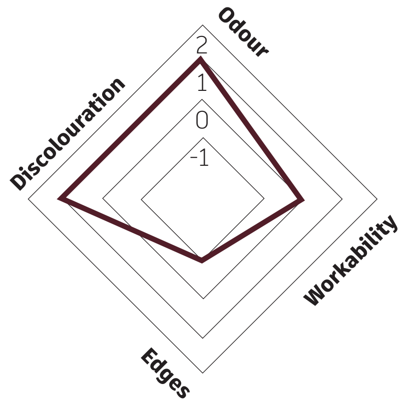


1.0% KD

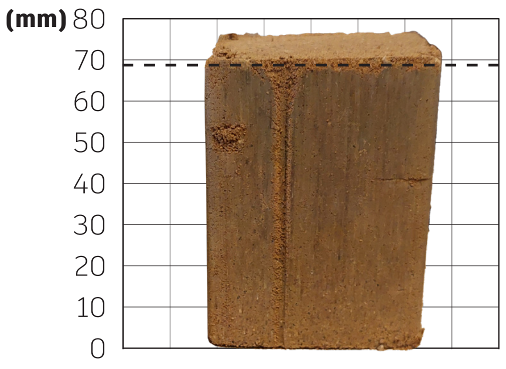


Density
~2112 kg/m3

Drying time
~3 days

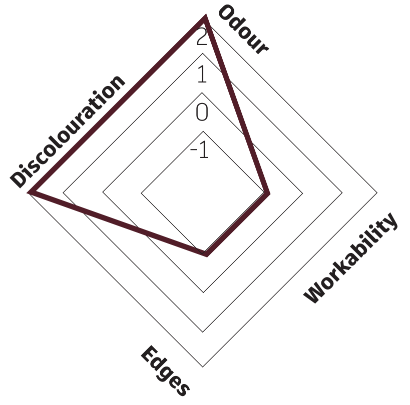


4.0% KD



Density
~2115 kg/m3

Drying time
~3 days



Compressive Testing

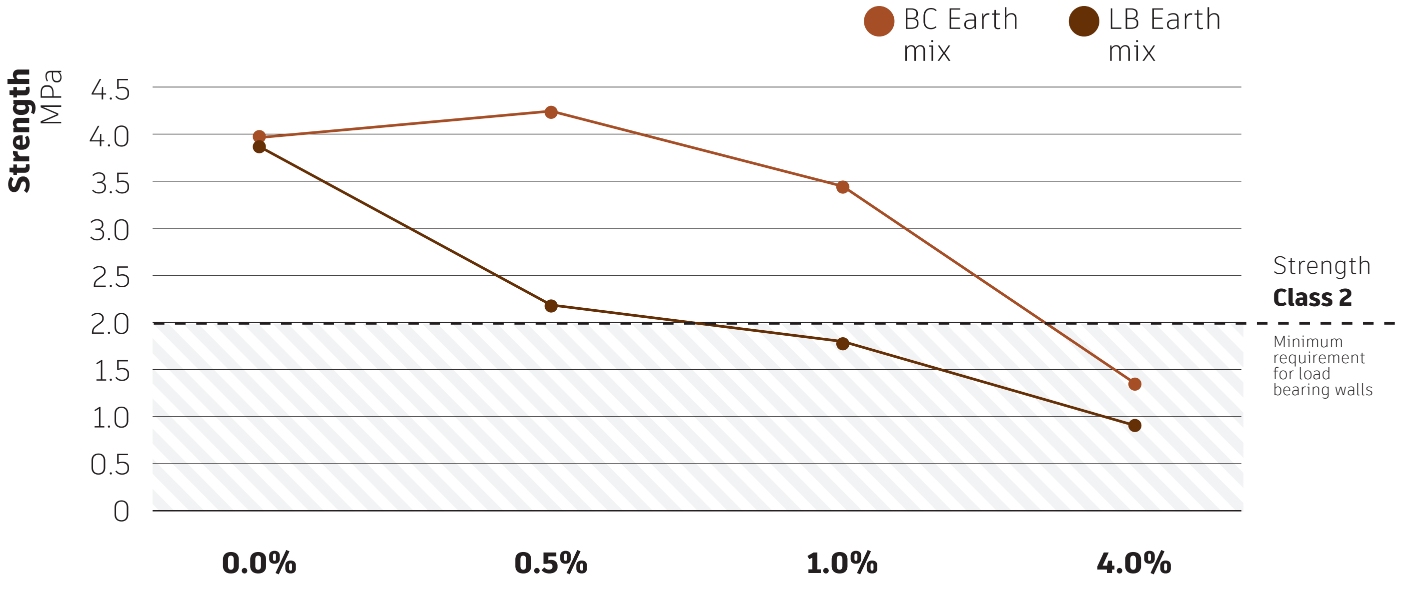
An initial compression testing round was performed on these samples - 0.5, 1.0, 4.0 % - to determine the mechanical performance of the suggested binder concentrations and to allow for comparison of quantitative experimental properties in addition to the aforementioned observed properties.

Compression testing was conducted on BC and LB earth mixes compressed at 20MPa. Both mixes were compared at this stage as there was sufficient material and it was deemed relevant to compare binder performance in earth mixes with different mineral compositions. All samples followed the expected failure pattern for well graded brittle materials, with an hourglass shape resulting from material loss only on the side rather than top and bottom faces. The results are graphically represented below.

All of the highest content [4%] samples were significantly weaker than their low content counterparts, indicating that this is beyond the optimum threshold. The 0.5 % binder content, on the other hand, indicated some strength improvement in the BC sample while for LB samples the baseline was by far the best performing. All 1.0% samples exhibited a slight drop in strength compared to the 0.5%.

Water Resistance Testing

Durability testing was not performed for this preliminary series.



Discussion

While not encouraging, the experimental findings align with the observed properties and indicate that a more feasible range may be concentrated around the lower percentage. It was determined that the 4% content could be excluded from subsequent test series and that experimental formulations should center around the most performant binder content [0.5%]. The range of investigated binder concentrations was therefore revised to reduce the maximum binder content to 1.0%, while an additional lower concentration was introduced at 0.25%. Series 2 [s2], discussed in the next section, therefore investigates the following concentrations: 0.25%, 0.50%, and 1.00%.

Series 2
[S2]

Comparing dry vs gel binder formulations

Earth Mix LB

Binder %
of dry soil wt.

Dry [KD] ●
Gel [KG] ○

	● 0.25	0.50	0.75	1.00	2.00	4.00
●	●	●		●		
○		○ 5%		○ 10%		
○		6.50 **[0.50]	9.70 **[0.75]	13.00 **[1.00]	26.00 **[2.00]	

Sample Compaction 6.8
MPa

No. Samples 6
of each concentration 3 Compression + 3 Water

** Dry solids equivalent, at 7.7% gel concentration

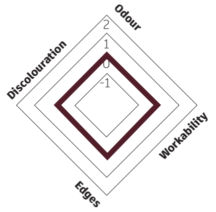
The aim of this series was to evaluate how dry and gel binder formulations compared to each other, assessing the effectiveness and similarity or difference between these formats. Binder concentrations were informed by the previous preliminary investigation [see results for series 1]. At this stage, the exact solid content of the gel was not known so the gel contents investigated are based on an assumption of approximately 10% solids. This translates to an equivalent solid content in KG 5% and KD 0.5% as well as KG 10% and KD 1%. The dry test series was performed prior to the gel series and, given the poor performance of the KD 0.25% formulation - which was almost indistinguishable from the baseline - it was assumed that this represented a sub-threshold dosage and was therefore excluded from the gel series.

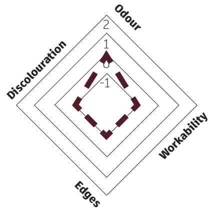
Observed Properties

Quantitative properties, including drying time and density, were extensively documented for this series. Generally, samples with higher binder concentrations were heavier but also less dense. This was primarily due to differences in volume, with KD samples in particular exhibiting reduced compaction ie. as in the previous series there is correlation between binder content and sample height. In terms of qualitative properties, the samples behaved as in the initial series with the additional observation that the 0.25% formulation remained effectively odourless and visually indistinguishable from the unstabilised earth mixture. The gel binder [KG] samples display notably improved aesthetic qualities, with clean edges, smooth surfaces and little discolouration. It can also be confirmed at this stage that increasing additions of both dry and gel binder result in a notably different earth mix consistency, with a much finer grain and less tacky or 'wet' feeling texture in formulations with higher binder concentrations.

0.00%

Mean Density
2,142 kg/m^3
Drying
—●—

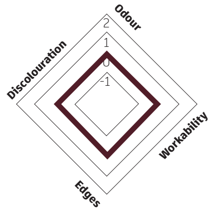




Target

0.25%
KD

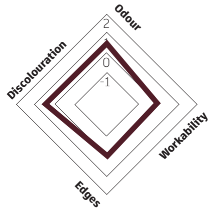
Mean Density
2,098 kg/m^3
Drying
—●—



0.50%
KD

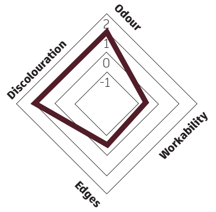
Mean Density
2,051 kg/m^3
Drying
—●—

image
missing

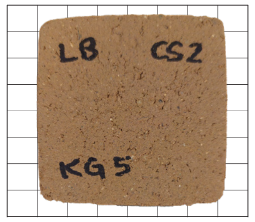


1.00%
KD

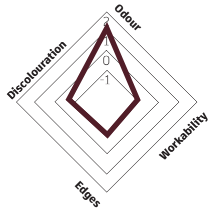
Mean Density
2,030 kg/m^3
Drying
—●—



5.00%
KG

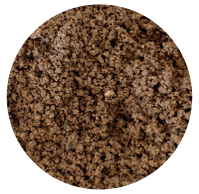


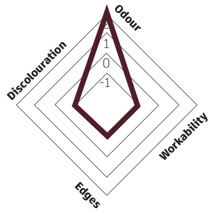
Mean Density
2,078 kg/m^3
Drying
—●—

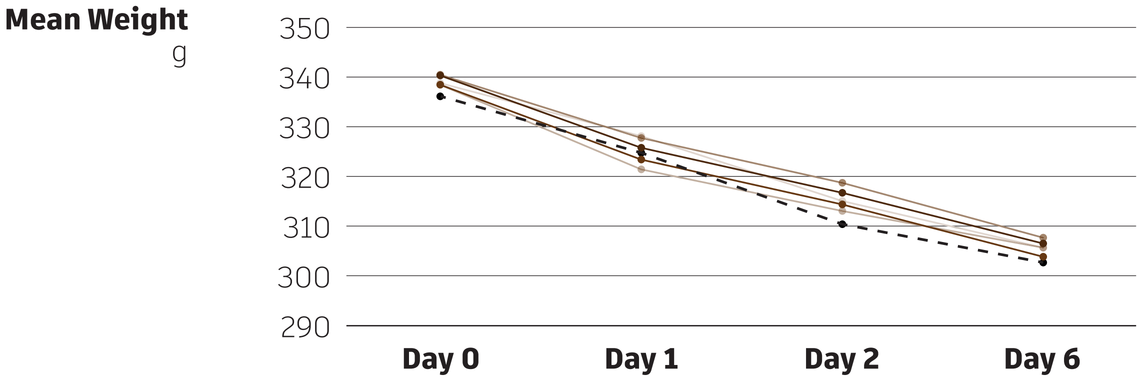


10.00%
KG

Mean Density
2,060 kg/m^3
Drying
—●—







Compressive Testing

In this series, sets of three samples per concentration were prepared according to the testing procedure. Results for each binder formulation can therefore be contextualised with a maximum, minimum and mean value. The test results for baseline and dry binder [KD] formulations are very scattered, with large standard deviation between samples in the same set. This indicates likely human error in manufacturing and renders the data unreliable, to an extent invalidating the results. It can nevertheless be observed that the trend approximates the findings of the first series, with increasing dry binder content correlating to reduced strength. Samples made with the gel [KG], on the other hand, are not only significantly less scattered but also indicate a positive trend with strength increasing as binder content increases. The mean strength for KG 10% samples represents a 32% increase on the mean un-stabilised baseline strength. All gel samples also fall comfortably above the target strength class of 2MPa, defined in DIN and NF standards as the minimum for load bearing masonry (DIN 18945 ; NF XP 13-901). Finally, it should be noted that while this series is reported as relating to LB earth mixtures only, some individual gel [KG] samples were also made using the BC earth mixture. This was identified as the most performant in the initial series so despite limited material availability it was deemed relevant to evaluate the gel binder [KG] with this earth mixture by making single samples for each gel concentration. Both gel concentrations investigated were highly performant, resulting in significant strength increase at 21% and 48% respectively for the KG 5% and KG 10% samples compared to the BC baseline established in the previous series. These findings are graphically represented in Appendix 01.

Water Resistance Testing

The dry [KD] and gel [KG] formulations were tested in successive rounds as the samples could not all be made concurrently. At the time of testing for KD samples the material required for immersion testing was not yet available so this test could not be performed. Immersion testing data is therefore limited to gel samples only, whereas submersion is assessed for both.

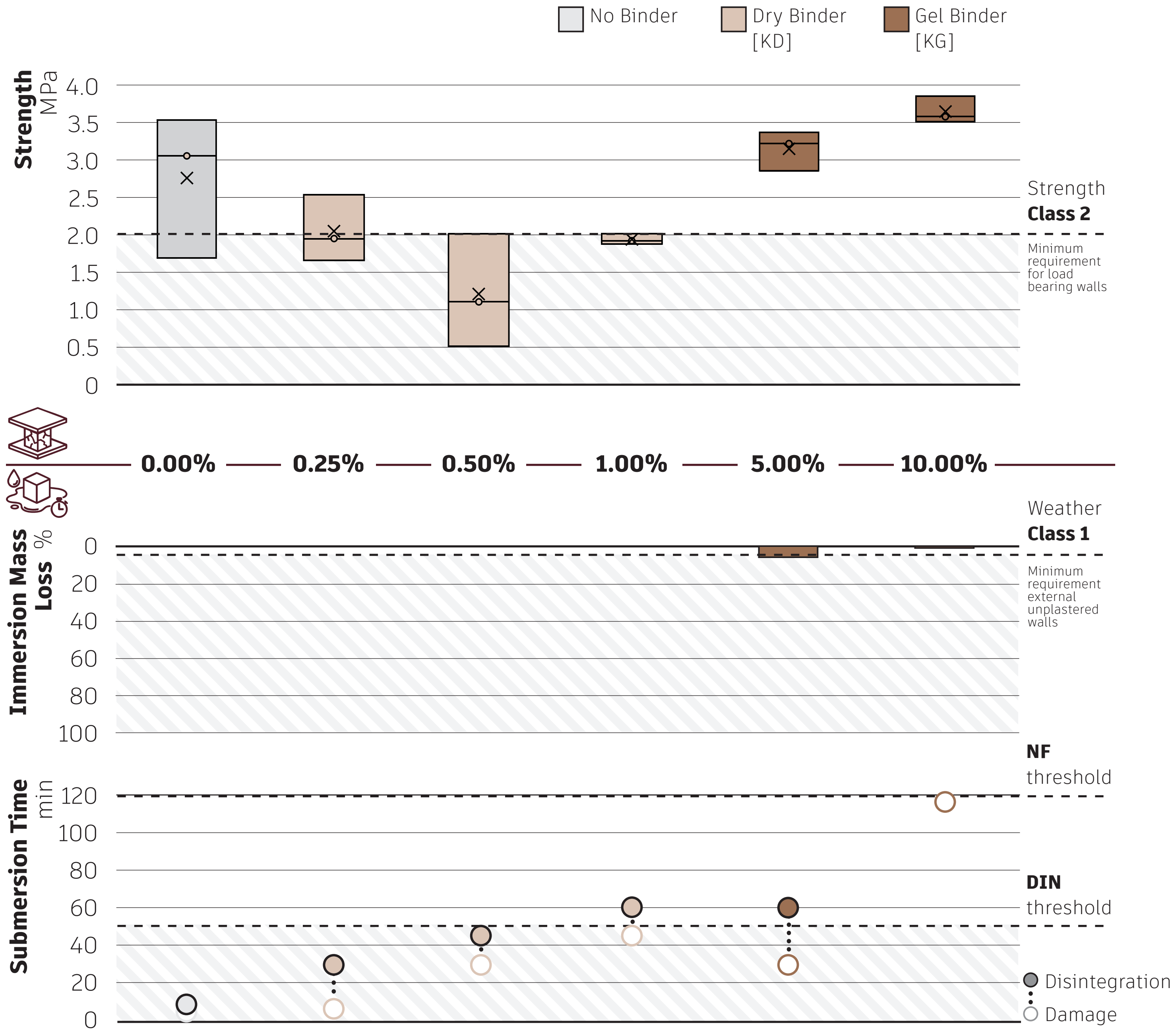
In contrast to the scattered compression data, the water resistance results are clear and consistent. All binder additions, both dry and gel, result in increased water resistance. While the dry binder [KD] samples demonstrate significant improvement compared to the baseline and the KD 1% exceeded the 45 min submersion time to disintegration, the gel samples remain notably more performant. Both KG sets exceeded the 45 min submersion threshold. The KG 10% samples in particular not only fell well below the target 5% mass loss threshold for category I exposure, but also remained sufficiently intact that following 120 min of submersion they could be easily handled without collapse so were retrieved and left to dry.

Discussion

Several possible hypotheses emerge from these findings and informed the design of subsequent test series.

The excellent water resistance and unusual observed properties of the stabilised earth mixtures – including differences in workability and compaction behaviour – suggest that significant polymer–water interactions may be occurring within the material system. This behaviour could also explain the reduced strength exhibited by the KD samples, which contain EPS as pure dry solids rather than hydrated in a gel. The introduction of this potentially disruptive element may hinder clay hydration, which is a primary mechanism determining the binding strength of earthen materials. At this stage it was hypothesized that mixing the earth and water before adding the binder and allowing for a 12h 'curing' period – as suggested in numerous references including Minke (2025) – may therefore be beneficial. This approach was not previously deemed necessary, being reported in literature as an optional strength improvement method. Numerous studies investigating the use of hydrogel forming biopolymers in earthen materials also omit this step as the formation of gel networks in the hydrated and compressed earth during drying is one of the primary mechanisms attributed to improved strength (Losini et al, 2021). Nevertheless, some biopolymer soil stabilisation studies such as Ouedraogo et al. (2020) do include a 'curing' stage. Given the unusual properties demonstrated by the EPS stabilised mixtures in this study, curing was introduced in the subsequent series.

The other notable outcome from this dataset is the large scatter observed in the compressive testing data. Scattered compression data is not unusual for earth blocks, with very high standard deviation reported by Lan et al., (2021) and Aubert et al. (2015), both studies dealing with methods to standardise compressive strength testing of CEBs. This can likely be attributed to material brittleness and inherent imperfections in the earth mixture. These may be both external, with surface roughness impacting measured data, as well as internal, with small defects resulting in generalised failure as is typical in brittle materials. To mitigate surface friction effects the compression testing procedure was amended by adding a small stack of paper between the samples and the testing plates, in lieu of Teflon sheets which could not be procured. To mitigate internal imperfections such as voids literature suggests increased mixing time to achieve a more homogenous material and align the clay minerals (Minke, 2020), however, the established mixing protocol could not be extended without additional equipment such as an electric mixer. As this was not available, and the reduced scatter in the second batch [KG] reinforced likely human error accounting for the earlier imperfections, the established procedure was deemed sufficient.



Series 3
[S3]

Binder formulations with commercial earth pre-mix

Earth Mix						**OSK**
Binder % of dry soil wt.					Dry [KD] ●	Gel [KG] ○
●	**0.25**	**0.50**	**0.75**	**1.00**	**2.00**	**4.00**
		● ○		● ○	● ○	
○		**6.50** **[0.50]	**9.70** **[0.75]	**13.00** **[1.00]	**26.00** **[2.00]	
Sample Compaction MPa				**7.1**		
No. Samples of each concentration				**5** 3 Compression + 2 Water		

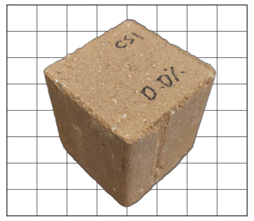
** Dry solids equivalent, at 7.7% gel concentration

This series explored the addition of binders in a commercial earth pre-mix with a much lower clay fraction than the earth mixes previously investigated. The earth mixture was delivered pre-moistened at 'optimum' water content. This allowed for testing of the hypothesis that dry binder [KD] additions might be better incorporated into an already hydrated earth mix that had been 'cured' overnight. However, this also meant that water content could not be adjusted to account for additional liquid content form the gel binder, so all gel [KG] formulations incurred a water content far exceeding the optimum. The aim had been to investigate an additional higher binder concentration as the previous series indicated that 0.25% KD had negligible effect while 10% KG was highly effective. The specific solid concentration of the gel (7.7%) was also established at this stage. Binder formulations were thus revised to : 6.5% KG equivalent to 0.5% KD, 13.0% KG to 1.0% KD, and a new concentration was added at 26.0% KG with equivalent 2.0% KD.

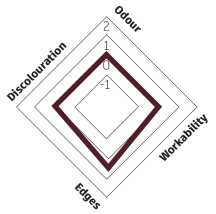
Observed Properties

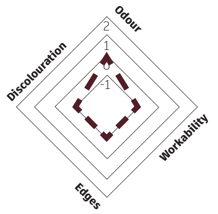
Before embarking on sample fabrication a small quantity of the earth mixture was dried to establish the existing ('optimal') water content which was determined to be 5%. During the mixing phase of sample preparation it became evident that the higher gel formulations would be compromised as they represented a notable excess of liquid. This earth pre-mix had significantly lower clay content than mixes used for previous series so the high gel concentrations resulted in a pasty texture with drastically reduced workability. During sample pressing the highest gel [KG] binder content was so liquid that it could not be adequately compacted without material spurting out from the moulds. Several samples subsequently collapsed during de-moulding and ultimately the remaining samples were discarded before testing as they began to grow mould after three days of drying in ambient conditions. In all other respects the observed properties aligned

0.00%



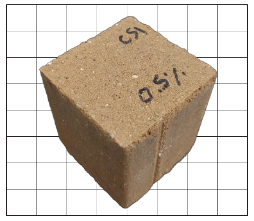
Mean Density
1940 kg/m3
Drying
–●–



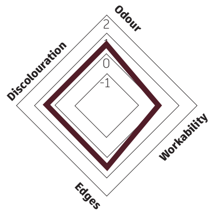


Target

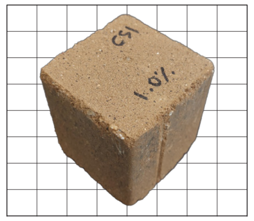
0.50%
KD



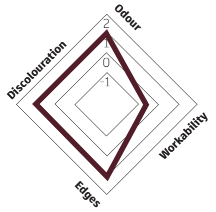
Mean Density
1916 kg/m3
Drying
–●–



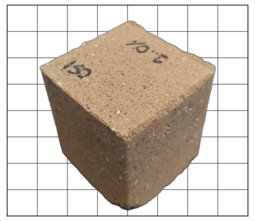
1.00%
KD



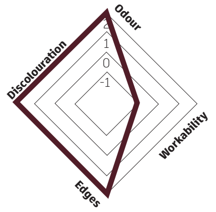
Mean Density
1878 kg/m3
Drying
–●–



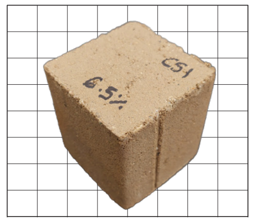
2.00%
KD



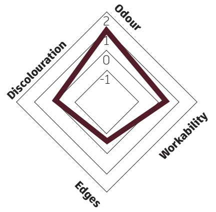
Mean Density
1858 kg/m3
Drying
–●–



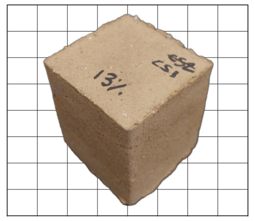
6.50%
KG



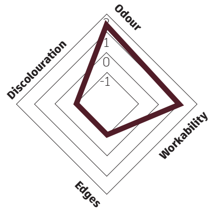
Mean Density
1963 kg/m3
Drying
–●–



13.00%
KG

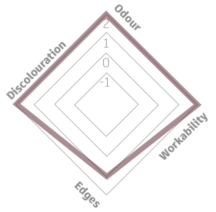


Mean Density
1862 kg/m3
Drying
–●–

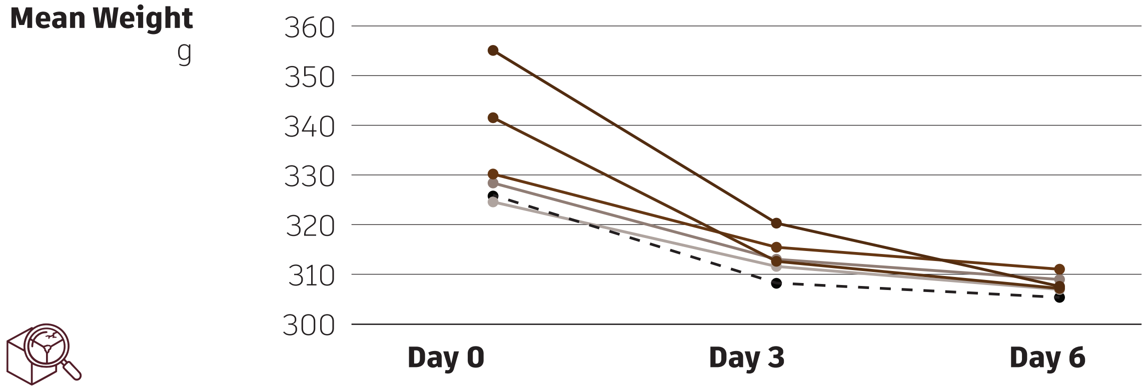


26.00%
KG

Mean Density
N/A
Drying



✖ **All samples discarded**



with findings from previous series, although the dry binder [KD] mixtures exhibited exaggerated versions of these characteristics. For example, dry binder [KD] content correlated to increasingly fine-grained texture and the finished samples were more discoloured.

Compressive Testing

This round of compressive testing definitively confirmed that dry EPS [KD], when incorporated following the methodology established in this project, is not effective as a binding agent in earth mixtures. Despite the added curing step the experimental results continued to indicate decreased mechanical performance in relation to dry binder [KD] addition. The gel binder [KG] formulations contrasted with previous findings in that, while the lower gel concentration (6.5%) showed a slight improvement, the KG 10% content resulted in a drastically reduced compressive strength compared to the baseline. These samples also exhibited more plastic behaviour during failure, with a shallower gradient and a second peak in force after initial failure, as can be seen in the applied force graphs in Appendix 02. As previously described, samples made with the newly introduced additional gel content at 26% were discarded due to mould growth before testing.

Water Resistance Testing

Water testing data followed a similar trend as in the previous series. Increased binder content resulted in improved water resistance, although dry binder samples were notably less performant than in the previous series. Samples made with the gel binder [KG] exhibited almost no mass loss during immersion. In contrast, un-stabilised baseline samples and those with only 0.5% KD completely disintegrated within the 10 min immersion timeframe. This complete failure occurred despite the samples being in direct contact with the water over less than half of their surface area.

Discussion

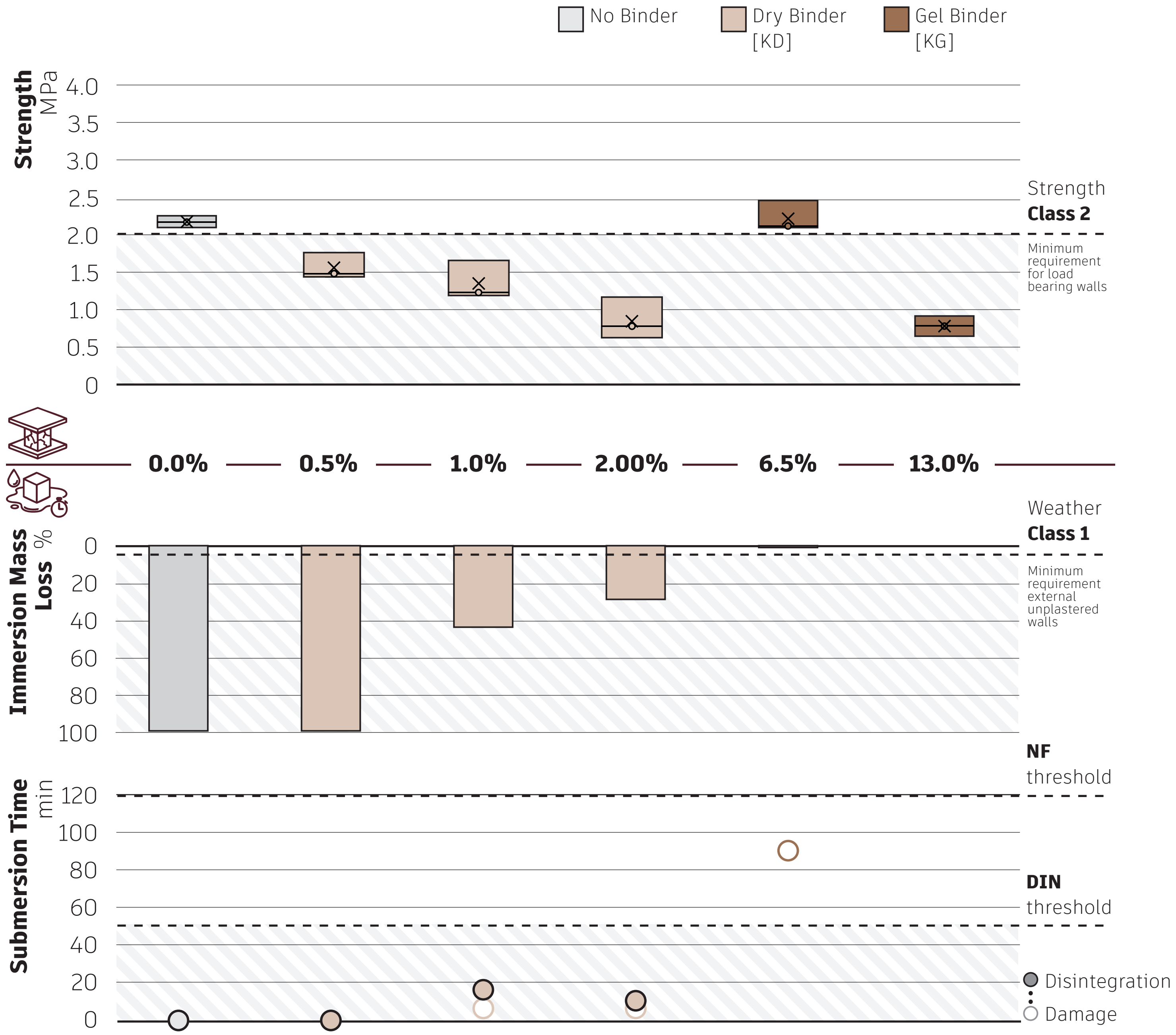
All compression testing results for this series are lower than those defined previously, this can likely be attributed to the soil grading and moisture content – with lower clay content resulting in reduced binding force.

Due to continuing poor performance of the dry binder formulations [KD] these were henceforth excluded from subsequent test series. The poor performance exhibited by the KG samples in this series was attributed to the excessive liquid content which, beyond disrupting manufacturing, likely introduced 'wet pockets' and weak points. It is also documented in literature that excessive polymer concentrations in soils can result in adverse effects and compromised strength through numerous mechanisms including electrostatic interactions and lubrication between soil particles (Latifi et al., 2016).

On the other hand, the success of the water resistance testing for this series underscores that even when mechanical strength is severely compromised EPS remains consistently performative for improving water resistance.

At this stage it was hypothesised that optimum gel binder addition may be related to the optimum water content of the soil mixture. The KG 6.5 % exhibited a slight improvement on the baseline while higher concentrations did not. This binder addition, which represented a total liquid content in excess of 200% the 'optimal water', was assumed to be close to the maximum threshold for this soil mixture.

Given the contrasting results obtained from this series – which may be explained by a host of differing uncontrolled variables – the fourth and final test series was designed instead as a simple extension of the second test series. The intended outcome was to corroborate the findings relating to improved performance with gel binder additions by demonstrating correlation through a set of three (rather than two) increasing gel binder formulations. An additional gel content was introduced between the two previously explored, at 9.7%.



Series 4
[s4]

Validation of Selected Binder Concentrations

Earth Mix LB

Binder % of dry soil wt.

Dry [KD] ●
Gel [KG] ○

● 0.25	0.50	0.75	1.00	2.00	4.00
	○	○	○		
○	6.50 **[0.50]	9.70 **[0.75]	13.00 **[1.00]	26.00 **[2.00]	

Sample Compaction MPa: 7.1

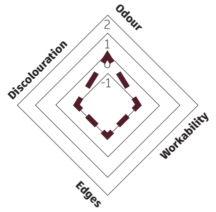
No. Samples of each concentration: 5
3 Compression + 2 Water

** Dry solids equivalent, at 7.7% gel concentration

The aim of this final series was to definitively demonstrate the correlation between increasing gel binder concentration and improved mechanical and durability performance of stabilised earth blocks. Accordingly, the same soil mixture used in the previously successful series [s2] was repeated, together with the previously identified performant binder formulations (with concentrations adjusted according to known solids content). The only intentional modification was the introduction of an intermediate third concentration to more clearly establish a performance trend. Nevertheless, the modified manufacturing procedure established in the previous series [s3] was retained rather than reverting to the approach used in [s2]. This procedural difference represents an additional variation relative to the original successful series and, as discussed in the following sections, is considered the most likely cause of the subsequent compromised performance.

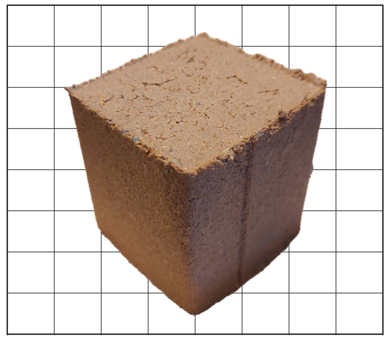
Observed Properties

The samples prepared for this series exhibited no unusual properties and generally followed the established trends. Samples with higher gel binder [KG] content exhibited smoother surfaces, cleaner edges, minimal discolouration and a mild but perceptible odour. It was, however, observed that the mix workability became particularly fine grained after being left over-night and that some of the bagged mixtures had slightly 'clumped' or hardened. During sample preparation this was not initially considered indicative of significant material alteration, and the mixes were lightly reworked by hand before being placed into the moulds. Sample drying could not be monitored for this series as it occurred during a week of campus closure for national holiday.

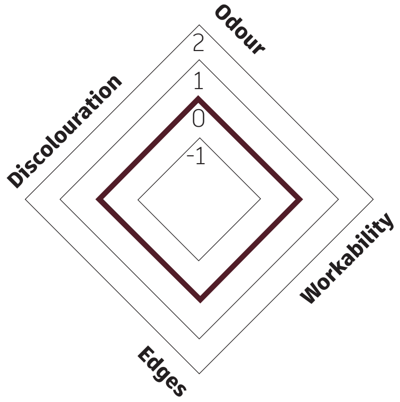


Target

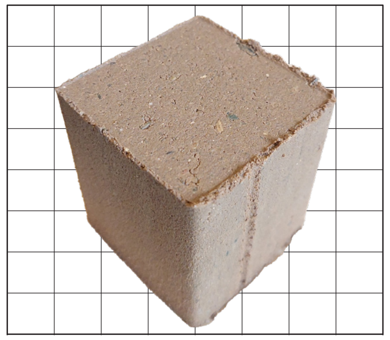
0.00%



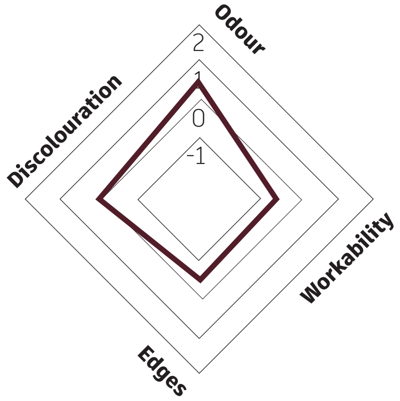
Mean Density
2000 kg/m3



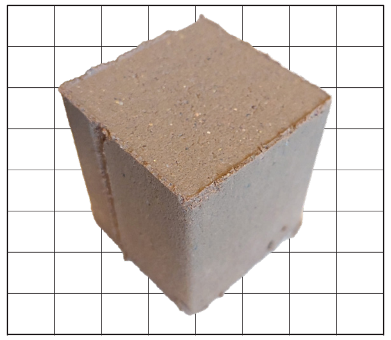
6.50%
KG



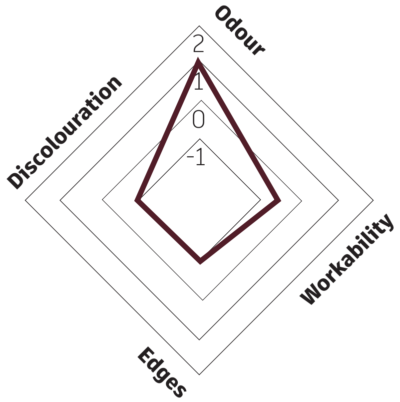
Mean Density
2002 kg/m3



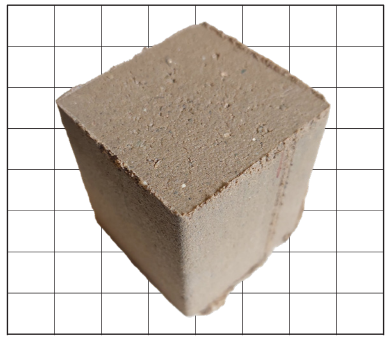
9.70%
KG



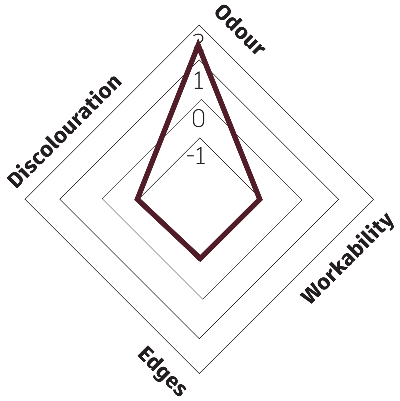
Mean Density
1995 kg/m3



13.00%
KG



Mean Density
1988 kg/m3



Compressive Testing

Compressive testing results for this series were notably inconsistent with the findings from series [s2]. Gel binder [KG] additions displayed a clear trend towards reduced mechanical performance, with the KG 13% sample having a 27% lower average strength than the baseline. The decline in strength is less drastic than trends observed in earlier series, and none of the average strengths for KG samples in this series fall below the 2MPa threshold for load bearing masonry. The limited data scatter indicates that this inverse trend in strength values is not a result of manufacturing defects but rather a failure mechanism not previously encountered. Several possible hypotheses are proposed in the discussion.

Water Resistance Testing

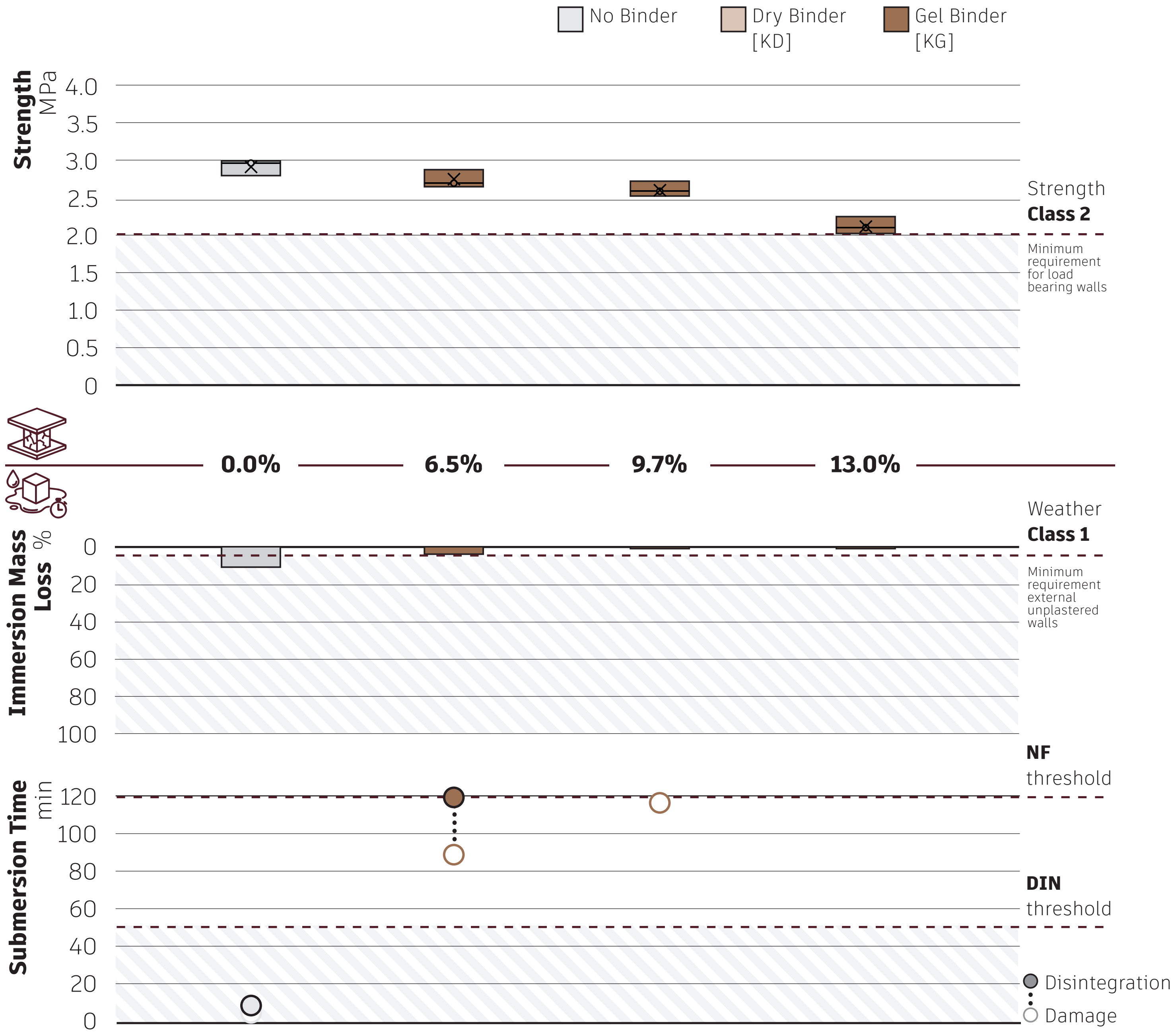
As in all previous series, the water resistance performance of samples with increasing binder content correlates positively. All gel binder formulations surpassed the 5% immersion loss threshold for category 1 exposure. The baseline samples in this series were notably more performant than those in the preceding series [s3]. This likely derives from the higher clay fraction and density of these samples compared to the commercial earth pre-mix.

Discussion

Due to the time constraints of the research programme, this series constituted the final stage of experimental testing. As such, this study was not able to conclusively demonstrate the anticipated positive binding effects of the EPS gel on compressive strength. Two possible explanations for the performance of this series are presented.

The primary hypothesis for the observed negative correlation between strength and binder content is that the gel interacted with the loose soil particles before compaction, preventing formation of a strong interconnected matrix during pressing. Gelling biopolymers typically increase the strength of earthen materials by creating a stabilising network within the soil microstructure or through increased bonding and electrostatic interactions with clay particles (Losini, 2021; Sesay et al., 2025). In this case, these mechanisms may have been initiated prematurely during overnight curing, coating the loose particles and inhibiting effective bonding once compacted into blocks. This is in direct opposition to the effects of 'water curing' on un-stabilised earth mixes, whereby the process enhances binding force as a result of electrochemical attraction between hydrated clay particles (Minke, 2025). However, it does mirror the properties of cement stabilised soils which must be used directly after binder addition as setting begins immediately (ibid.)

Another possible explanation for the observed results is the degradation of the Kaumera EPS gel. The gel was left in a sealed container in ambient conditions throughout the experimental phase, which amounted to almost four months. Despite the inclusion of a preservative it is not recommended that the gel be subjected for such long periods to fluctuations in temperature and relative humidity. Given the extended exposure and, in particular, the elevated temperatures of the final month (late spring) it is possible that biologically active components within the gel degraded or began to ferment. This may have altered the soil–polymer interaction and negatively affected binding efficacy.



Synthesis

Observed Properties

Aesthetic & Sensory Properties

Aesthetic properties generally improved alongside binder addition, with samples exhibiting smoother surfaces and reduced surface cracking after drying. Dry binder [KD] formulations, however, resulted in visible discolouration, with speckling and streaking becoming increasingly pronounced at higher binder concentrations. This discolouration was not observed in gel binder [KG] formulations. Instead, these samples displayed smooth surfaces, negligible cracking, and sharp, well-defined edges until a critical binder threshold was exceeded. Beyond this point, excessive gel binder content caused the earth mixture to transition towards a plastic-like state, negatively affecting workability, compaction behaviour, and dimensional stability.

Sample malodour also increased noticeably with rising binder content. All dry binder [KD] samples above 0.5% exhibited a perceptible odour even after drying, although this remained mild below 2.0% concentration. Gel binder [KG] samples generally produced a slightly stronger odour than their powdered counterparts; however, this remained only faintly perceptible unless the samples were closely inspected. The only formulations which produced an intense odour sufficient to permeate the surrounding room were KD 4% and KG 26%. In addition to the characteristic Kaumera smell, the latter also had a pronounced smell related to mould growth which occurred during drying.

Note KD 4% and KG 26% excluded from overview matrix due to sample failure

Mixed dry binder [KD] and water

Settled dry binder [KD] in water

Gel film [KG] on mixing implement

Hydric Behaviour

Throughout the course of this project, the tested binder formulations demonstrated unusual and frequently contradictory water interaction behaviours. This is not entirely unexpected, as EPS is reported in literature to be amphiphilic, exhibiting both hydrophobic and hydrophilic characteristics. The suspected hydrophobic behaviour of the dry binder [KD] – which altered earth mix texture and workability – was investigated by mixing the powdered binder with water. After several weeks of submersion and repeated mixing the powder still had not dissolved, demonstrating insoluble hydrophobic behaviour. This was not expected given that the EPS is extracted in hydrogel form ie. suspended in water, however, consultation with Kaumera confirmed that the material becomes hydrophobic once dried. It is therefore plausible that the reduced compaction observed in samples with higher KD content, together with the finer grained texture of these mixtures, may be associated with these hydrophobic properties.

In contrast, the gel binder [KG] remained viscous and fully hydrated throughout several months of experimental testing. Some unexpected observations are nevertheless noted, in particular the film forming ability of gel coatings. When accidentally left to dry on a metal mixing implement, the gel formed a hard, plastic-like film that could not be removed through washing or mechanical friction. The coating was only detached after exposure to very hot water, whereupon it flaked from the surface. Such behaviour is atypical for many water-soluble gelling biopolymers and indicates more complex film-forming or cross-linking mechanisms within the suspended EPS gel.

Mould Growth

Mould growth was observed in both dry binder [KD] and gel binder [KG] samples when binder concentrations were elevated. This indicates the existence of a critical threshold above which biological degradation becomes problematic. The dry powdered binder [KD], when submerged in water to investigate solubility behaviour, also produced a thin mould film on the water surface, despite the material itself remaining undissolved. This behaviour is consistent with a phenomenon reported in discussions with the artist Billie van Katwijk, who described clay mixtures containing high concentrations of Kaumera as “rotting” during ceramic experimentation.

Importantly, samples below certain binder concentration thresholds exhibited no visible mould growth, even after prolonged exposure to water or extended immersion testing. In particular, all samples containing gel binder concentrations above 10% remained structurally intact after two hours of submersion and, once removed and left to dry under ambient conditions, showed no subsequent signs of mould formation. These observations suggest that mould development is not solely dependent on moisture exposure, but is likely influenced by a complex interaction between binder concentration, water availability, aeration, and the biological stability of the EPS material.

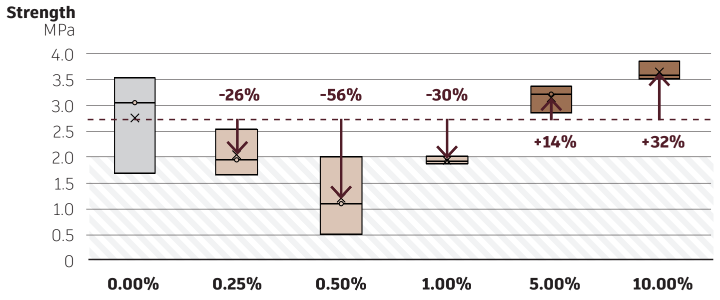
The observed material properties exhibited clear trends. Increasing gel binder [KG] content generally improved surface quality and reduced visible cracking, although excessive additions resulted in adverse effects such as malodour and mould growth. These improvements were less pronounced in dry binder [KD] formulations, while discolouration and dimensional instability became more evident. The contrasting hydric behaviours of the two binder formats suggest that EPS interacts with earth through complex mechanisms not yet understood. Nevertheless, these observations provide valuable insight into performance limits and demonstrate that binder concentration plays a critical role in determining the experiential qualities of the material.

- ✓ Samples with gel binder additions are significantly smoother, sharper edged and more homogenous in appearance than unstabilised baseline samples.
- ~ While smell is unpleasant, this remains very mild at low concentrations (particularly with KD formulations) and even at higher contents such as KG 13% is only perceptible upon close inspection
- ~ Hydric behaviour is complex and results in contrasting water interaction behaviours affecting workability and compaction.
- ✗ Biological degradation and mould growth appears in samples with elevated binder content in both formats (KD and KG) over a relatively short time.

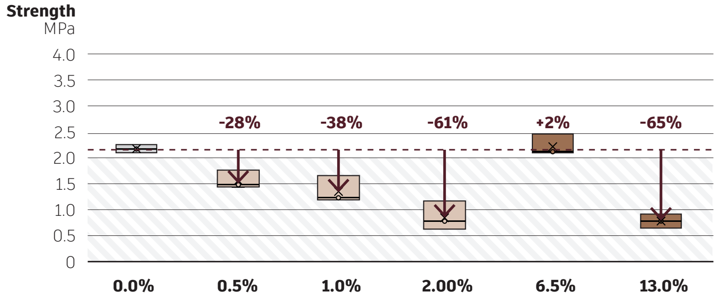
Synthesis

Compressive Strength

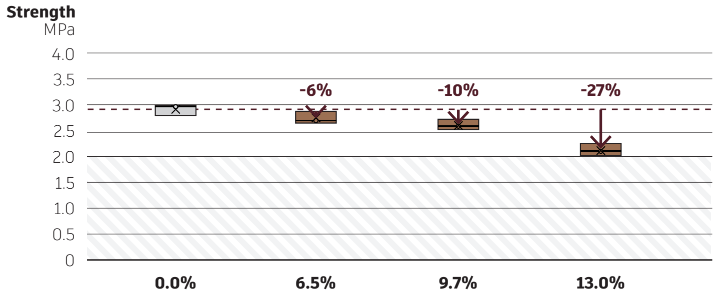
Series 2 **[s2]**



Series 3 **[s3]**



Series 4 **[s4]**

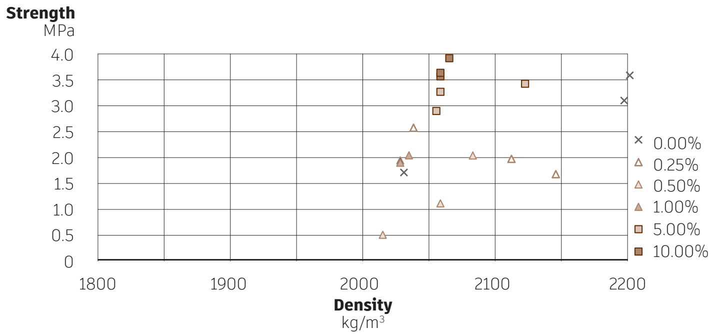


☐ No Binder ▨ Dry Binder [KD] ■ Gel Binder [KG]

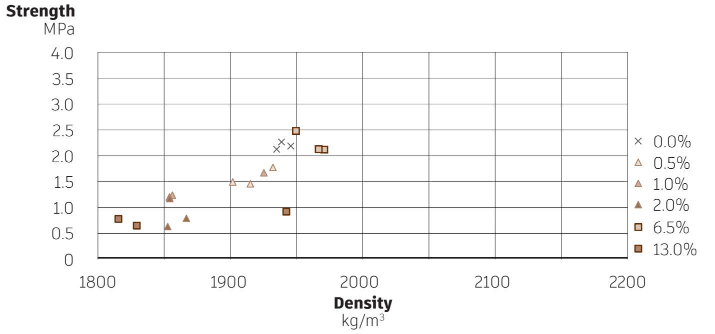
Strength and scatter

Observed failure behaviour during testing was generally brittle, characterised by a sharp loss of strength at failure (see appendices 02 and 03 for detailed force/time graphsfor each series). Early series exhibited significant scatter between samples, likely resulting from manufacturing inconsistencies and internal defects. As the research progressed this scatter reduced, with the final series having a very minimal standard deviation. This is attributed primarily to reduced human error in sample preparation, although it is also notable that in general the gel bound [KG] samples exhibit less scatter – possibly due to more uniform material homogeneity and binder distribution. In general, a clear negaive correlation is observed between increasing dry binder [KD] content and strength, while for gel binder [KG] formulations two distinct and opposing trends are observed in series 2 and 4 while series 3 shows no correlation.

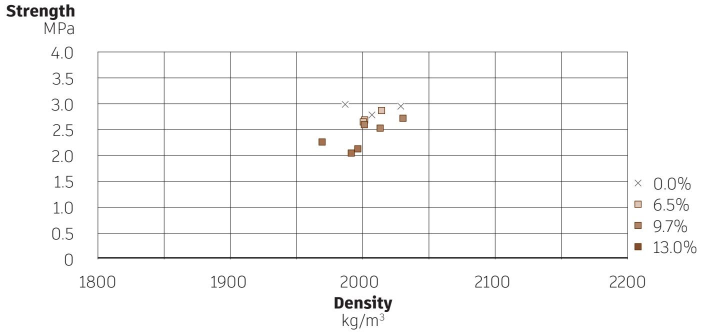
Series 2 **[s2]**



Series 3 **[s3]**



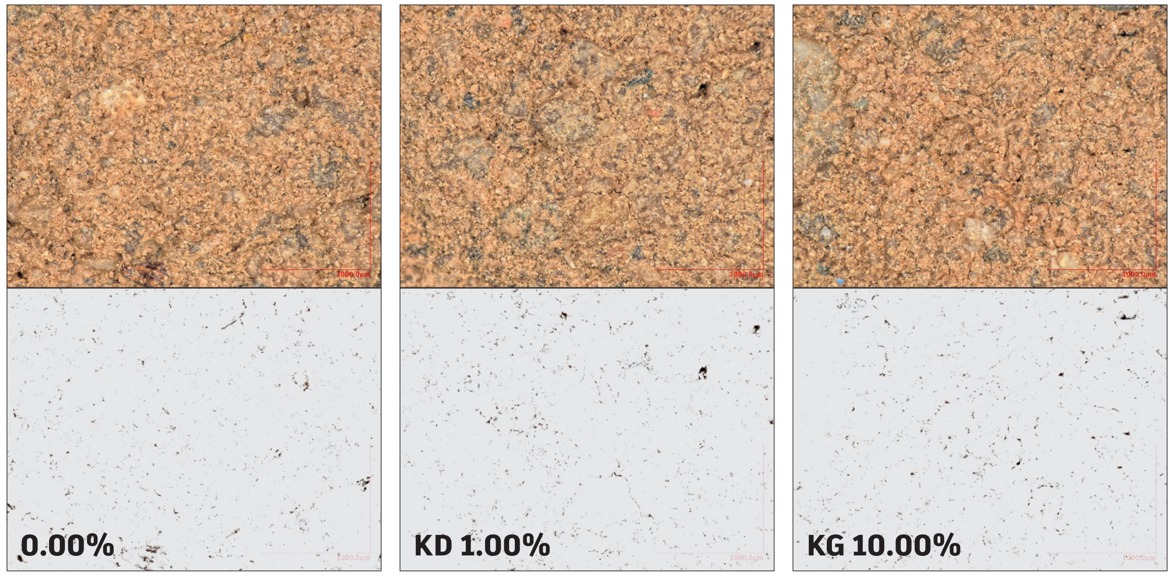
Series 4 **[s4]**



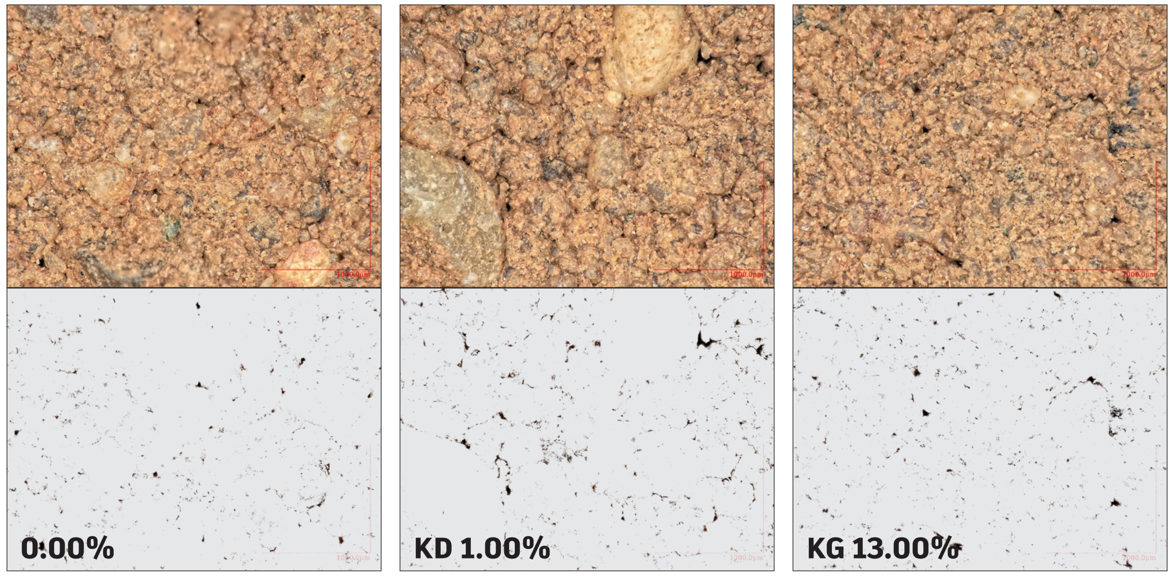
Strength and Density

The graphs plotting strength against density suggest that these two parameters do not correlate. A possible exception is in the case of series 3, for which it does appear there is a positive trend. Nevertheless, this does not exclude that the strength results observed may also have been determined by the hypotheses previously put forward : excessive liquid content and lubrication, particle size distribution, reduced clay fraction and sub-optimal water content. Density is also increasingly consistent across successive series, with variation between samples in the final series being very limited, again suggesting improved manufacturing and reduced human error. It can therefore be reasonably assumed that other mechanisms related to polymer-soil interactions are the primary determinants of recorded strength. Given its complex molecular composition, EPS has the potential to influence soil behaviour through several mechanisms commonly associated with different classes of biopolymers. Polysaccharides are known to form stabilising gel networks and enhance interparticle bonding; proteins can promote flocculation and aggregation of clay and silt particles; while lipid components may contribute hydrophobic surface coatings (Sesay et al., 2025). As EPS contains varying proportions of these different constituents, its behaviour cannot readily be attributed to a single stabilisation mechanism, and the relative contribution of each remains unclear.

[S2]



[S3]



Microscope Imagery

To further analyse and compare results, microscopy images were taken of selected crushed samples from the best and worst performing series. The images present equivalent solid contents for dry and gel binder formulations as well as a baseline, and display the internal structure of the specimens at 100× magnification. These are shown alongside processed versions highlighting visible voids in black on grey. Although this magnification is insufficient to identify particle-scale mechanisms such as gel network formation, particle coating, or specific soil–polymer interactions it is adequate for identifying larger voids, pore structures, and internal imperfections.The microscopy images reveal noticeable differences between the tested mixtures. In particular, the OSK earth mix samples from Series 3 exhibit a greater number of larger voids, often concentrated around coarse aggregate particles. This observation may partially explain the comparatively lower compressive strengths recorded for these specimens. Conversely, the best-performing sample, KG 10% from Series 2, displays the fewest and smallest visible voids. This finding supports the hypothesis that improved pore filling, enhanced interparticle bonding or gel matrix formation may contribute to the observed increase in mechanical performance.

Strength and Curing

While adverse effects were observed in Series 4 for samples pressed after overnight curing, as discussed in the corresponding section, the broader influence of curing time was not investigated within this study. Owing to project time constraints, all specimens were tested after a standardised drying period of seven days. This approach aligns with DIN and NF testing procedures for compressed earth blocks, where specimens are considered ready for testing once dry mass has stabilised. Many studies on biopolymer-stabilised soils, however, report strength development over curing periods of 14 or 28 days (Sesay et al., 2025). Unlike unstabilised earthen materials, biopolymer-stabilised materials may continue to develop strength through ongoing physical, chemical, and microstructural processes following compaction. It is therefore possible that the testing programme undertaken here did not capture the full extent of strength development associated with EPS stabilisation.

Little can be definitively concluded from the strength testing in this study. The wide-ranging and, in part, contrasting compressive strength results obtained throughout suggest that multiple stabilisation mechanisms may be acting simultaneously. The contrasting performance observed between test series further suggests that different variables may strongly influence which mechanisms dominate. A more detailed microstructural investigation would be required to determine the precise pathways through which EPS affects the strength of earthen materials.

✓ Highest strength improvement recorded is for KG 10% samples in Series 2.

+32% LB **+48%** BC

✓ Large scatter observed in early data is reduced drastically by final series.

✗ All dry binder [KD] formulations resulted in negative strength correlation.

✗ Recorded strength trends for gel binder [KG] formulations are contradictory across series, with positive correlation in series 2 and negative in series 4.

Synthesis

Water Resistance

Stability in Static Water

Durability testing demonstrated consistently positive performance across EPS-stabilised samples. Gel binder [KG] formulations were particularly effective, with all specimens containing ≥6.5% EPS successfully recovered after 120 minutes of submersion and subsequent drying. Overall, repeated improved immersion resistance indicates a clear positive correlation between increasing EPS gel content and enhanced resistance to water-induced degradation.

This behaviour may be attributed to multiple interacting mechanisms. More broadly, the unusual hydric behaviour of EPS likely underpins its effectiveness in improving water resistance. The lipid fraction may contribute to the formation of hydrophobic surface coatings, thereby reducing water uptake as reported by Sesay et al., 2025. Similarly, insoluble polymers like chitosan are associated with reduced hydraulic conductivity and improved erosion resistance due to their hydrophobic characteristics (Losini et al., 2021), this may be akin to the properties exhibited by the dry powdered EPS [KD]. In addition to hydric effects, microstructural improvements may further contribute to enhanced durability. Reduced surface imperfections and the mitigation of hairline cracking in KG samples are likely to limit pathways for water ingress which Minke (2025) highlights as a key indicator of long term durability.

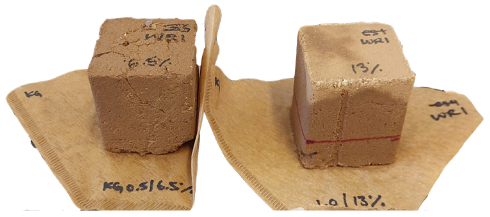
These findings further support the hypothesis of complex interactions between hydrophobic and hydrophilic components within Kaumera EPS. The consistency of the observed trends also suggests that water resistance may continue to improve with increasing binder content; however, it is unclear whether this relationship is subject to a performance threshold or instead constrained by practical limits such as maximum achievable binder inclusion without biological degradation.

KG **6.5%** KG **9.7%** KG **10.0%** KG **13.0%**

Failure Modes

Failure and disintegration behaviour provided particularly informative insight into stabilisation mechanisms. In contrast to unstabilised baseline and KD samples, which typically disintegrated into loose, non-cohesive soil upon saturation, gel stabilised formulations failed in a markedly different manner. Rather than disaggregating, these samples tended to fracture into coherent “chunks,” indicating the retention of internal cohesion even under prolonged submersion. While some surface degradation was observed (for example, in one case a surface aggregate was displaced), the overall structural integrity of the samples was maintained even when fully saturated. Ultimate failure was generally characterised by progressive scaling and the detachment of larger sections, particularly at edges and corners. However, the main body could be physically retrieved from the water in a consolidated state, with minimal visible swelling. These observations indicate a transition in failure mode from granular disintegration to cohesive structural degradation with increasing binder content.

An additional notable observation was the accelerated drying behaviour of higher-binder samples [see image below of KG 6.5% (left) and KG 13% (right) immediately after and 1hr after retrieval from submersion testing]. This suggests that increased EPS content may influence not only resistance to disintegration but also post-saturation moisture transport and drying kinetics.



All stabilised formulations demonstrated clear positive correlation with water resistance compared with unstabilised samples, although gel binder [KG] formulations were significantly more performant. Increasing KG content was associated with enhanced cohesion, reduced disintegration, and a shift in failure mode from granular breakdown to coherent chunking and edge scaling. Samples with higher binder content also exhibited faster drying behaviour, suggesting altered moisture transport. These results indicate that EPS improves both short-term resistance to saturation and longer-term durability.

- ✓ Water resistance was consistently improved with all tested binder formulations.
- ✓ Trend and positive correlation are clear across all test series.
- ✓ All KG formulations above 5% outperformed the class I immersion loss threshold for weathering exposure and remained intact throughout 120 mins of submersion.

<1% Average immersion mass loss for KG 13% samples

06.

Outlook

Product Applications

Proposed product applications are derived from the experimentally observed material characteristics, following a material-driven design approach. Key established properties include improved aesthetic quality (reduced surface cracking, smooth and homogeneous surface finish, and sharper edge definition) and enhanced water resistance. The reduction in surface cracking is also relevant to long-term durability, as surface cracks are recognised as key pathways for water ingress and indicators of increased susceptibility to frost damage (Minke, 2025).

Improved aesthetics
smooth surface,
sharp edges

Improved water resistance

On this basis, applications that benefit from both weather resistance and controlled surface aesthetics are considered most suitable. Drawing on contemporary earth construction practices, the following material-oriented applications are identified.

Erosion checks – often used in contemporary earth architecture as calculated markers of wear and weathering, as well as intentional aesthetic expressions of material aging (Martin Rauch & Lehm Ton Erde Baukunst GmbH, 2020).

External plaster – while internal earth based plasters and finishes are widespread, external use is limited by susceptibility to weathering. Additional protective coatings are often required and sharp edges or corners must be carefully detailed (typically rounded or lipped with rigid element) (Minke, 2025).

Roadway and railway sound barriers – applications of earthen materials in infrastructure are uncommon, however, this particular application has risen to prominence (in the Netherlands) through a 2021 innovation contest funded by ProRail and Rijkswaterstaat aimed developing sustainable alternatives to conventional acoustic barriers. Among the selected concepts was a 3D-printed (shot-earth) earthen noise barrier developed by Terrestrial, which has since progressed into ongoing development and prototype testing (Earthen Noise Barrier Summum Engineering, 2025). Given the stringent structural and durability requirements of such infrastructure elements, this represents a particularly demanding application; however, it also offers substantial impact potential due to the widespread deployment of noise barriers across both urban and rural environments.

Figures 16-18. Images of proposed applications generated with Gemini AI. Inspired by reference images from the credited projects: Rammed Earth House by Tuckey Design Studio (2026), Rauch House by Martin Rauch (2008), Narbo Via Museum by Fsoter + Partners (2020), Earthen noise barrier by Terrestrial (2021)

Rammed Earth House
United Kingdom, Tuckey Design Studio, 2026

Rauch House
Martin Rauch, Austria, 2008

Erosion Checks

The high water resistance and well-defined edge stability of EPS gel-stabilised earth make it well suited for erosion protection components. Such elements could be integrated into rammed earth construction as protective layers or detailing at vulnerable junctions. This would provide an alternative to conventional stone, rock, or tile-based protection systems commonly used to mitigate weathering at corners and sharp edges. In addition, these elements may also function as deliberate architectural features, as demonstrated in the referenced works. The small volume of erosion stops required relative to the volume of a wall is also an advantage in the context of mitigating possible negative side effects from the inclusion of EPS, notably odour.


Narbo Via Museum
Foster + Partners, France, 2020

Weatherproof external plaster

Given its improved durability in wet conditions, EPS-stabilised earth may also be suitable for external clay plaster applications. The material's smooth finish and sharp edge definition could be further exploited for surface detailing, including embossing or ornamental relief. While such applications are common in vernacular earth construction, contemporary earth architecture often relies on stabilised systems to achieve more precise geometries with refined, linear detailing. Comparable aesthetic outcomes are currently achieved using highly cement-stabilised systems such as SIREWALL (as in the referenced example).


Earthen Noise Barrier
Terrestrial, Netherlands, 2021-ongoing

Infrastructure Sound Barrier

A more complex and ambitious application would be the use of EPS-stabilised earth in acoustic barrier systems. These structures are exposed to environmental conditions but are not typically subject to direct user contact, reducing the significance of material characteristics such as residual odour. Although earthen noise barriers remain a relatively novel application, growing interest in bio-based infrastructure demonstrates increasing precedent for their adoption. Given the extensive scale of transport infrastructure networks, this application offers considerable potential for impact. Furthermore, infrastructure projects generate substantial quantities of excavated soil, creating opportunities for material reuse. The combination of waste-derived earth and wastewater-derived EPS presents a particularly compelling circular-economy model, enabling the valorisation of two residual waste streams within a single construction product.

Industrial Relevance and Market Potential

Direct comparison with cement-stabilised earth - the current industry standard - was beyond the scope of this research. Consequently, no definitive conclusions can be drawn regarding the relative performance of EPS and cement stabilised formulations under identical conditions. Nevertheless, a broader comparison provides useful context for evaluating the potential applicability and market relevance of EPS as a soil stabiliser.

Although higher cement contents can substantially improve the mechanical strength of earthen materials, low cement additions may interfere with clay bonding and reduce strength (Minke, 2025). The principal objective of cement additives is thus not strength enhancement but rather improved durability and resistance to weathering (ibid.). In this regard, the performance of EPS-stabilised soils observed in this study suggests that EPS may represent a promising alternative.

However, cement-stabilised earth is commonly subjected to significantly more demanding testing regimes than those employed in this study. For example, Norton (1997) describes procedures involving immersion periods of up to seven days, as opposed to the maximum 120 minutes tested in this study. While EPS-stabilised samples frequently remained intact over this period, many exhibited early signs of surface degradation, meaning long-term equivalence under prolonged saturation cannot be established. As such, the relative durability of EPS and cement stabilisation remains uncertain and represents a key area for future experimental work.

From a commercial perspective, EPS is not currently competitive with cement on direct material cost. Unmodified Kaumera gel is estimated at approximately €3–8 per kilogram of dry matter, corresponding to roughly €0.23–0.60 per litre of gel (A. Raja, personal communication, 05 May 2026). In contrast, a quick scan of cement prices at building suppliers in the Netherlands gives a range from €0.20–0.30 per kilogram, in other words, a tenth fraction of the price. However, cement is a mature, globally optimised construction material whose market price is shaped by established supply chains and policy-influenced markets, while EPS is a novel material venture for which cost of production will likely decrease with larger market adoption. For example, the 2023 Climate Bonds Initiative report on the cement transition relates that under the EU Emissions Trading System (ETS) free allowances cover up to 100% of cement industry emissions due to concerns over market competitiveness (Passaro, 2023). A full comparison would therefore need to consider both direct material costs and broader economic impacts.

Environmental considerations may represent a more significant area of potential advantage for EPS. Life-cycle assessment (LCA) data for Re-Plex, from a 2021 MSc thesis within TU Delft, indicates that Kaumera contributes a relatively small proportion of overall environmental impact despite comprising a substantial fraction of the material mass. For climate change impacts specifically, Kaumera accounts for ~8% of total emissions, corresponding to approximately 0.006 kg CO_2 per kg (Heijdens, 2021). Generalised data from the 2025 edition of the ICE carbon database lists concrete emissions as several orders of magnitude higher, at 0.81 kgCO2e per kg (Circular Ecology, 2025). While these results are promising, it is unclear whether the scopes of these LCA are equivalent and direct environmental comparison would require further comparative analysis.

Overall, while EPS cannot currently be considered commercially competitive with cement on a cost basis, its encouraging durability performance and low environmental impact suggest meaningful long-term potential as a sustainable soil stabilisation material.

Figure 19. Images of cement and kaumera gel taken from google images

Conclusions

This research investigated **how wastewater-derived extracellular polymeric substances (EPS) can be employed as a bio-based stabiliser for earth construction**. The project sought to address a recognised knowledge gap regarding secondary bio-based materials as alternatives to cement stabilisation.

The experimental results demonstrate a clear positive correlation between EPS content and water resistance, although the mechanisms through which it operates remain only partially understood. This was a consistent finding across all test series for both dry and gel binder formulations, which significantly improved durability under immersion. Gel-based formulations demonstrated particularly strong performance and remained intact after prolonged submersion, with all but one concentration test exceededing established water resistance thresholds for compressed earth blocks. These findings suggest that EPS has considerable potential as a durability-enhancing stabiliser for earthen materials.

The mechanical performance results were less conclusive. While certain test series demonstrated substantial increases in compressive strength, subsequent testing produced contradictory outcomes, indicating that strength development is highly sensitive to variables such as binder format, concentration, curing regime, and manufacturing procedure. The wide variation in results suggests that multiple stabilisation mechanisms may be acting simultaneously and that the relationship between EPS and soil behaviour is more complex than initially anticipated. Further microstructural and long-term investigations are therefore required before definitive conclusions regarding strength enhancement can be drawn.

Beyond the measured performance criteria, the study identified a range of consistent material behaviours associated with EPS incorporation. Increasing gel binder content generally improved surface quality, cohesion, and reduced cracking during drying, while excessive additions produced adverse effects including reduced workability, odour, and biological growth. The contrasting behaviours observed between dry and gel formulations further highlighted the complex hydric characteristics of EPS and their influence on performance.

Despite these uncertainties, the research demonstrates the **potential of EPS as a high-value application for an abundant secondary resource** recovered from wastewater treatment. Compared with conventional cement stabilisation, EPS offers the prospect of significantly reduced embodied carbon and elimination of primary raw material extraction for the binder component. An important area for future research remains the assessment of recyclability for EPS-earth materials, which could not be experimentally verified within the scope of the present study but would present a further competitive advantage against cement-stabilised earth. In this respect, the project **contributes** not only **to reducing the impact of contemporary earth construction** through development of sustainable binder alternatives, but also to broader circularity efforts aimed at transitioning waste streams into valuable construction resources.

The proposed applications explored within this study - including erosion control products, exterior earth plasters, and infrastructure-scale earth elements - illustrate practical contexts in which enhanced water resistance may be more critical than maximising compressive strength. These applications suggest that EPS-stabilised earth may already possess sufficient performance for certain non-structural and semi-structural uses, even while further optimisation is required for load-bearing applications. More broadly, the results indicate that **EPS stabilisation has the potential to expand the range of architectural and engineering applications available to earth construction** by addressing one of its principal limitations: vulnerability to water exposure.

Ultimately, this research is an exploratory investigation into a novel material system. Nevertheless, it establishes a promising foundation for future work and demonstrates that wastewater-derived EPS has potential within the next generation of circular, bio-based construction materials. At a time when the construction industry must simultaneously reduce carbon emissions, minimise resource extraction, and valorise waste streams, the convergence of earth construction and wastewater-derived biopolymers represents a compelling direction for further research and innovation.

Reflections on the Graduation Process

This graduation project was a research-through-making investigation into the potential of a novel composite system. Rather than developing a predetermined proposal, the project adopted an exploratory approach. As such, the process was characterised by iteration and adaptation in response to findings that emerged throughout the research.

One of the most significant lessons was recognising the inherently uncertain nature of exploratory research. Unlike design projects with clearly defined outputs, experimental research often begins without knowing whether the investigated hypothesis will ultimately prove successful. Prior to this project, I had limited experience with this field and initially underestimated the extent to which the research direction would be shaped by the system under investigation. While not every experiment produced the anticipated outcome, the unexpected and sometimes contradictory results proved equally valuable in developing a broader understanding of the material and its behaviour.

A central challenge throughout the project was balancing scientific rigour with practical realities. The research sought to generate quantitative data that could be compared against existing literature and standards, however, the experimental work was undertaken with very limited equipment and laboratory infrastructure. Considerable effort was therefore required to develop testing procedures that were both scientifically meaningful and practically achievable. In many respects this tension reflects the nature of earth construction itself. Foundational texts on earthen building combine laboratory testing and engineering principles with highly practical field-based methods, where observations of workability, appearance, smell, and simple site tests remain important tools for behavioural characterisation.

Looking back, greater engagement with interdisciplinary specialist expertise at an earlier stage would have strengthened the research process. While valuable guidance was received from supervisors, laboratory staff, industry contacts, and external practitioners, identifying a dedicated earth construction specialist or material scientist at the outset could have provided additional technical insight and helped streamline aspects of the experimental programme.

The project was motivated from the beginning by environmental and societal objectives and did not, as such, raise major ethical concerns. However, the use of materials derived from wastewater treatment did raise questions regarding public perception and acceptance. Although these aspects could not be explored in depth within the scope of the project, they emerge as important considerations for future implementation and warrant further investigation.

The most significant methodological reflection concerns the relationship between the original design ambitions and the findings that emerged through experimentation. At the outset, the intention was to explore applications of EPS within digitally fabricated earth construction systems. As the research progressed, however, it became increasingly clear that this objective had been imposed upon the system rather than emerging from it. This realisation required a substantial shift in focus, with elements of the original digital fabrication agenda eventually becoming secondary to understanding the system itself. A more experiment-led approach, in which observed properties and behaviours informed subsequent design speculation, proved essential to developing meaningful conclusions.

While the project did not conclusively validate all of its initial hypotheses, it generated valuable knowledge regarding the behaviour of EPS-stabilised earth systems, identified promising directions for future research, and reinforced the importance of allowing findings to challenge initial assumptions and of remaining responsive to the evidence generated.

Future Work and Research Directions

The inconclusive nature of several findings in this study highlights the need for further investigation into EPS-stabilised earth systems. While the research has demonstrated promising trends in water resistance, a number of critical performance and environmental aspects remain insufficiently understood.

From a performance perspective, further work is required to determine **optimal EPS binder content**, as trends observed in this study were not conclusive. Related to this is the need to investigate the influence of **binder condition and ageing** (e.g. effects of fermentation and PH), particularly given that EPS is not an inert additive and may change in properties over time. Similarly, the **timing and sequence of processing steps** (e.g. delay between mixing and pressing) may significantly affect final performance and warrants systematic study.

Several **processing and environmental boundary conditions** were not explored but are likely to be influential. These include the effects of controlled curing environments (e.g. climate chamber conditioning, curing time and strength development), as well as the potential benefits of thermomechanical processing such as heat and compression, as used in other EPS-based composite systems. Such approaches may significantly alter bonding behaviour, odour development, and structural integrity.

A deeper **mechanistic understanding of EPS–soil interaction** is also required. Advanced characterisation techniques such as scanning electron microscopy (SEM) and X-ray diffraction (XRD) of both untreated and stabilised soils would help to clarify the dominant interaction mechanisms - as is common in earth stabilisation research literature. Future research should also examine how soil parameters such as particle size distribution, clay fraction, and mineralogy influence system performance and binder thresholds.

In addition, a **broader range of mechanical and durability testing** is required to fully evaluate engineering applicability. Standardised tests such as abrasion resistance, impact strength, freeze–thaw cycling, erosion under flowing water, vapour diffusion, and hygroscopic behaviour (including surface moisture absorption) were beyond the scope of this study but are critical for real-world validation. As are field weathering tests, with long-term exposure imposing service conditions that single immersion events do not capture. Of particular interest is corner and edge performance, which is a known failure point in earthen systems and was identified by consulted practitioners as a key limitation in complex geometries.

Another primary area for future work concerns **material circularity and end-of-life pathways**, which are central to distinguishing biopolymer-based stabilisation systems from conventional cementitious binders. In this study, recycling potential and degradation pathways of EPS within earthen materials were initially identified as key criteria but could not ultimately be assessed. More broadly, comprehensive life-cycle assessment is required, including embodied carbon, energy demand, and wider environmental impacts.

Environmental safety considerations also require attention. The **leachability and potential toxicity** of EPS-stabilised earth systems should be assessed in accordance with relevant standards (e.g. DIN and NF protocols), particularly given the increasing importance of waste-derived inputs in construction materials. Similar studies on sewage sludge-based building materials demonstrate that such assessments are essential for regulatory acceptance and long-term deployment (J. A. Cusidó & Cremades, 2012).

Finally, future research should address **material perception and acceptance**, particularly given the distinctive sensory and aesthetic properties of the system, including odour and its origin in wastewater-derived inputs. Structured evaluation using material-driven design frameworks such as the Ma2E4 toolkit (Camera & Karana, 2018) could provide valuable insight into user perception, acceptance barriers, and potential design strategies for normalisation of such unconventional material systems.

Back-matter

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Z

List of Figures

If not otherwise specified, figures and photographs were made by the author.

Figure 10. Project stages and chronological progression. Icons generated by Gemini AI or downloaded from Flaticon.com. Credits: Freepik, Soremba, iconfield, smashingstocks, monkik, xnimrodx, Muhammad Atif

Figure 11. Key properties to be experimentally investigated. Icons generated with Gemini AI.

Chapter 3. Opening Spread : Image taken by author.

Figure 12. Soil grain size distribution appropriate for earth blocks, adapted from Minke (2025)

Figure 13. Procurement map of primary materials with logos of respective organisations.

Figure 14. Drop test results. Figure reproduced from Norton (1997)

Chapter 4. Opening Spread : Image taken by author.

Figure 15. Satisfactory failures of cube specimens, adapted from NEN-EN 12390-3(2019)

Chapter 5. Opening Spread : Image taken by author.

Chapter 6. Opening Spread : Image taken by author.

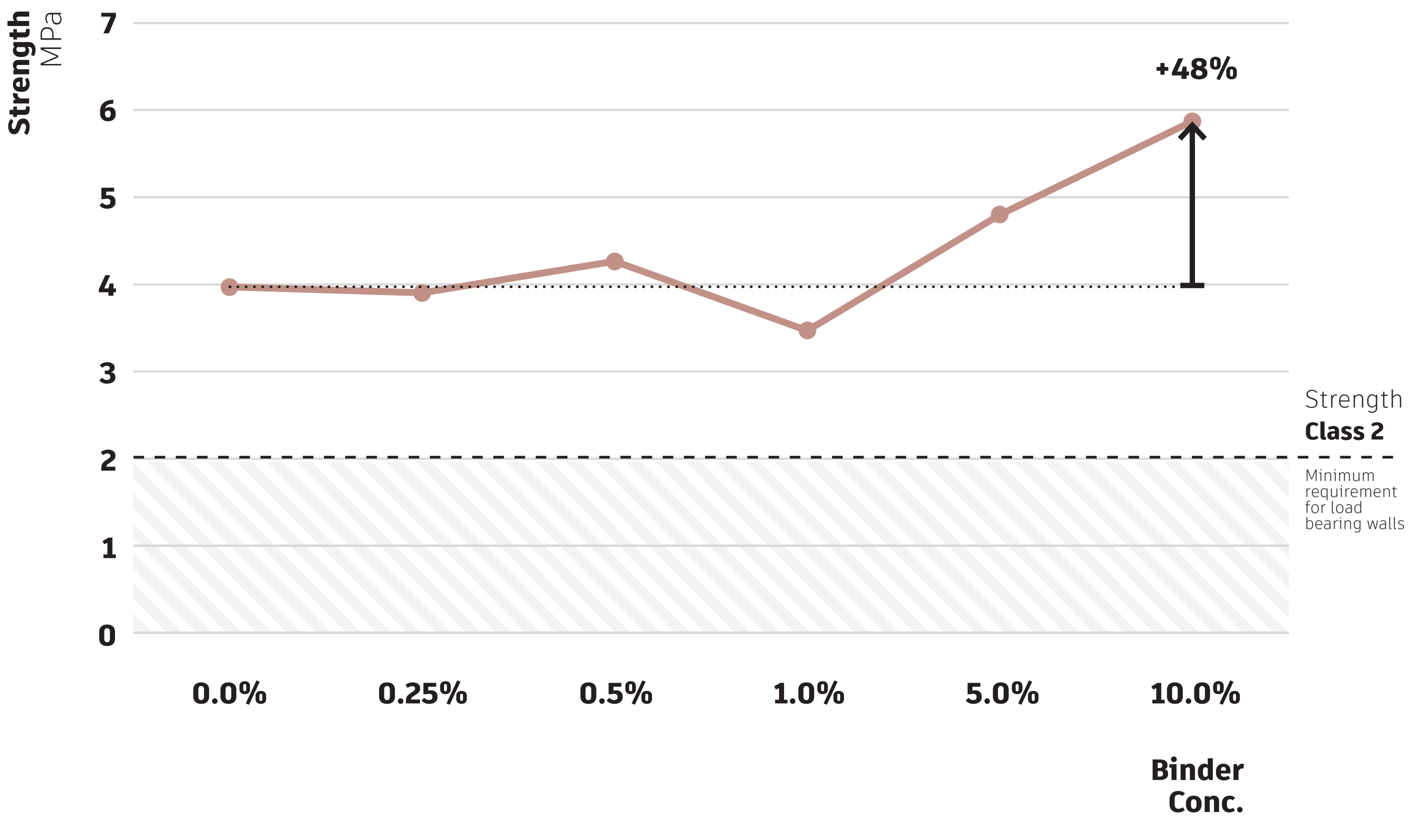
Figures 16-18. Images of proposed applications generated with Gemini AI. Inspired by reference images from the credited projects:

Rammed Earth House by Tuckey Design Studio (2026), Rauch House by Martin Rauch (2008), Narbo Via Museum by Fsoter + Partners (2020), Earthen noise barrier by Terrestrial (2021)

Figure 19. Comparison of kaumera vs cement. Images adapted using Gemini AI from: Achira22/Shutterstock.com and https://kaumera.com/en/about-kaumera/the-project

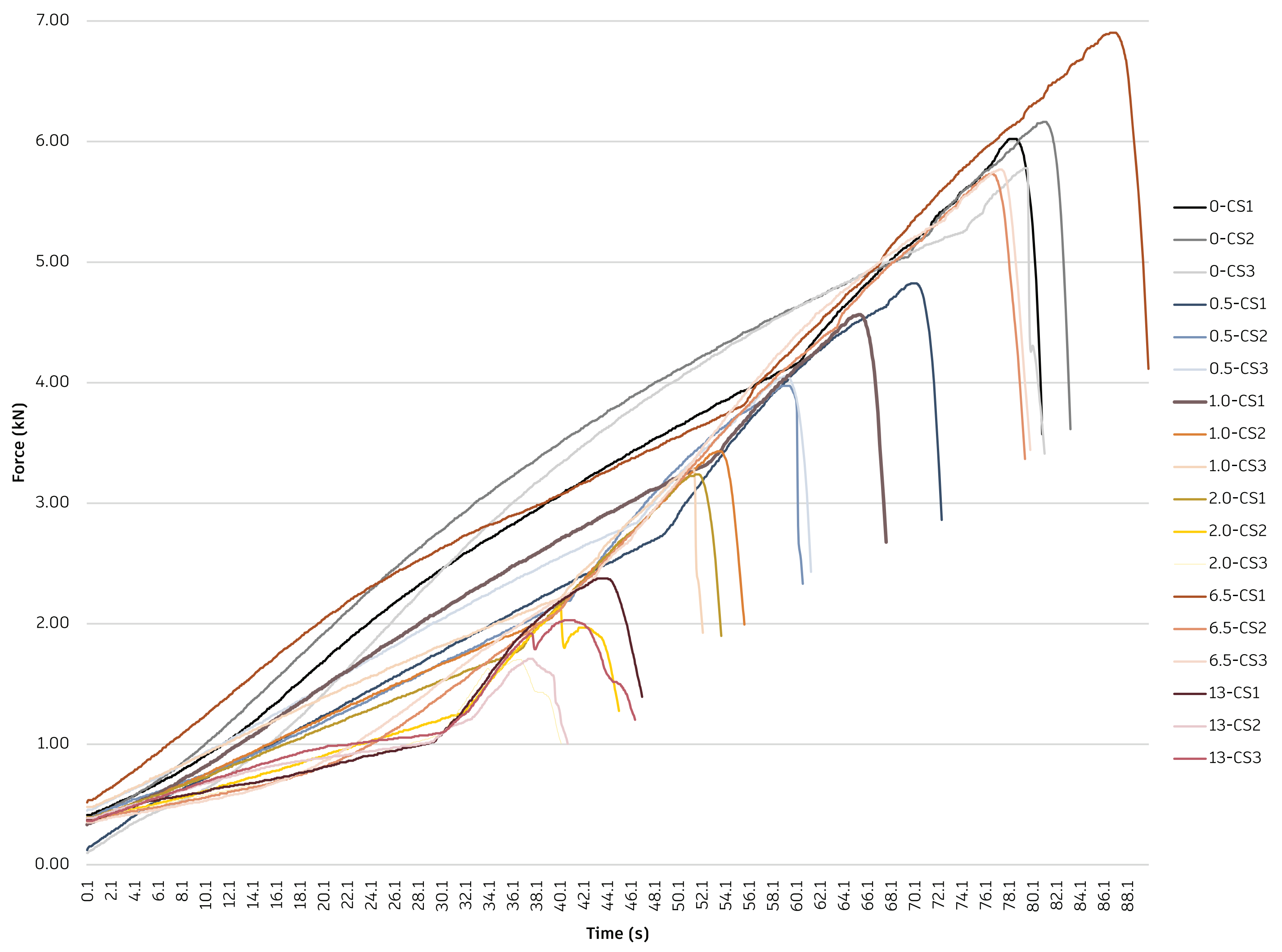
Appendix 01

BC Mix Compression Results



Appendix 02

Force vs Time Graph for Series 3



Appendix 03

Force vs Time Graph for Series 4