Bio-based Binders for Rammed Earth Construction:

Experimental research exploring the use of historic binders for future material implementation.

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1. Introduction

1.1. Context

The built environment is responsible for 37% of global carbon emissions. Although extensive measures are being implemented to reduce "operational carbon" (the carbon emissions being produced by building use) reducing "embodied carbon" (the carbon emissions being produced by building construction and material) receives significantly less attention (UNEP, 2023).

To reduce "embodied carbon", minimizing carbon emissions from building materials is crucial. Compared to non-bio-based materials, using bio-based materials reduces the carbon emissions by an average of 45% during the building's lifecycle (Zuiderveen et al, 2023).

To effectively implement bio-based construction materials, modern construction practices must be re-evaluated, as they often do not align with alternative construction methods nor materials. Often, this leads to the revaluation of heritage architecture and rediscovery of vernacular architecture (Birznieks, 2013). This can be explained by the fact that pre-industrial construction materials oftentimes meet the modern sustainability requirements (Spiegel, Meadows, 1999). Preceding the Industrial Revolution, the needs of the built environment were met solely by implementing locally available materials, that do not harm their environments during or after building use (Spiegel, Meadows, 1999).

One of the oldest building materials in use is raw earth; bio-based, available globally at a local level, and low-waste at all stages of use (Dethier, 2020). A promising construction technology of raw earth that is being re-developed for modern use is rammed earth construction. This technique can also be traced back to the beginning of building construction (Birznieks, 2013). One of the promising qualities of traditional rammed earth construction is it's potential to function fully circular; after use, the structure can be deconstructed to be re-implemented into new developments (Van Gorp, 2018).

Combining information on this widely used bio-based material, raw earth, with modern material knowledge allows for potential further sustainability improvement of the material (Zawistowski et al, 2020). By combining these two knowledge sources, this research aims to aid in the search for circular and eco-friendly construction materials and methods.

1.2. Problem Statement

After and during the Industrial Revolution, enormous population surges demanded a quick development of housing. In parallel, building materials were being redeveloped, providing in part the industrialisation of the Industrial Revolution. This provided mechanically produced materials and products like steel, concrete and brick (Sgouropoulou, 2013). To ensure the implementation of these novel techniques and materials was done in a safe manner, quality checks and product standardisation were developed.

The design possibilities and guaranteed quality modernised materials provided caused traditional construction material use to fade to the background. Therefore, quality checks were oftentimes not developed for traditional building materials, as demand was low (Sgouropoulou, 2013). This product testing and standardisation gave us construction norms for modern materials as we now know them. Because these new regulations were not made with traditional materials in mind, their use declined even more rapidly (Ganotopoulou, 2014).

As a result, not only did the use of historic materials decrease, the craftmanship used in heritage architecture disappeared from sight as well. Knowledge that traditionally got passed down from master to apprentice ceased to be given to the next generation of builders (Dethier, 2020). An example of this is the widely spread raw earth architecture of Britain traditionally being built by so called ‘mud masons’. These mud masons adhered to the rules of those before them, learning from experience and observation (Keefe, 2005). This now long-gone knowhow must be rediscovered to reintroduce the use of traditional building methods (Ganotopoulou, 2014).

One of the previously common materials that suffered the faith of dwindling use is raw earth (Dethier, 2020). Raw earth architecture has word-wide historic traditions (Jaquin et al, 2008). Despite raw earth being a sustainable and widely available construction material, a lack of national and international building norms specified to earth construction prevents current-day designers and engineers from choosing the material for construction (Canivell et al, 2020). One of the raw earth construction techniques that is affected by this lack of building code is rammed earth (Zawistowski et al, 2020).

Modern rammed earth constructions are often tested using norms originally developed for other materials, such as concrete, causing rammed earth construction not to meet the norms of the current built environment (Walker et al, 2010). To overcome this issue, a binder consisting of cement is often added to the material mixture, transforming the rammed earth into a stabilised material (Cockram, 2018). With the use of cement, the environmental benefits of rammed earth construction decrease (Taghiloha, 2013). The embodied energy of rammed earth construction increases linearly to the amount of cement in the mixture (Reddy & Jagadish, 2003). Furthermore, the use of cement in rammed earth prevents the material from being re-used (Van Gorp, 2018).

Although using cement to transform rammed earth into a stabilised material seems logical at surface level, un-stabilised rammed earth construction has been used for centuries (Jaquin et al, 2008). By requiring the cement stabilisation of rammed earth, the proven durability of rammed earth construction is disregarded. Consider examples as the Great Wall of China, or the Alhambra in Spain (Van Gorp, 2018). The construction methods of historic feats of all raw earth architecture techniques can provide needed knowledge for modern architectural engineers, allowing them to forego the use of cement as a binder.

Moreover, the historic use of bio-based binders in earth construction is commonly observed all over the world, with greatly varying binder types. Each individual binder allows for specific material properties to be altered in the final earth mixture (Maravelaki-Kalaitzaki et al, 2023). Even though this generational knowledge exists, it is poorly documented on and thus no longer frequently implemented for modern usage (Zeng et al, 2008). To reach the potential optimised performance of rammed earth construction, it is thus necessary to consider bio-based binders and their original functions in earth construction.

The conclusion that can be drawn from this all is that in-depth modern knowledge on historic earthen architectural techniques and material formulas is lacking, as well as modern building codes provided for traditional construction methods such as rammed earth. As a result, current use of rammed earth construction is not living up to its full sustainable and circular potential.

1.3. Research Objectives

The main objective of this research is to provide a first suggestion towards determining the most suitable biobased binders for the use in rammed earth construction. This is done to eventually allow rammed earth construction to fulfil modern strength and weathering building norms, without the addition of commonly used high carbon-emission binders, like cement (Eyeson, 2022). However, this research limits itself to initial findings of potential material improvement, rather than achieving material norm compliance. Substituting common binders with bio-based binders, will over time allow for full sustainable potential of rammed earth as a construction method and material in the future built environment (Taghiloha, 2013).

Rammed earth architecture

Research into both the modern and historic information available on raw earth architecture, with a focus on rammed earth, provides available knowledge for use of earth as a construction material. This knowledge contains both the technical information on the topic as well as the (historic) relevance and function of the material. Moreover, researching the known flaws of rammed earth construction can illustrate the necessary material property enhancement of modern rammed earth.

Historic bio-based binders

Research into the use of historic bio-based binders provides an overview of traditional binders suitable for material property enhancement of rammed earth construction. With this knowledge, a framework to compare said binders can be made. This framework can describe the historic binder use and their intended influence on the rammed earth performance. The advantage of studying historic binders is that previously discovered uses and properties of said binders can directly be implemented into modern research.

Modern implementation bio-based binders

The research on rammed earth architecture provides an overview of the necessary enhancements of the material properties of rammed earth. The research on historic bio-based binders provides an overview of their known influence on rammed earth material properties. By comparing the necessary enhancements of rammed earth with the known enhancements provided by historic bio-based binders, suitable bio-based binders can be determined. Experimental research can provide a first suggestion towards the most suitable bio-based binders, and the overall effectiveness of the use of bio-based binders in modern rammed earth construction. Through experimentation the initial performance of the considered rammed earth mixture can be compared to the altered performance of the same rammed earth mixture with added bio-based binders.

1.4. Project Scope

To determine the scope of this research, the same categories as mentioned in chapter *1.3. Research Objectives* can be used. Two additional categories, that of the main objective of this research and the project location, must be added.

Location of research

To be able to test the samples and prototypes made in this research against current material requirements and building norms, a location must be chosen. The location this research considers is Northwestern Europe. This consideration is made since most of the countries in this region share the same marine west coast climate: mild summer temperatures, minus winter temperatures, and consistent (heavy) rainfall (Boudrea et al., 2023). Additionally, this region includes the advanced German and French building norms for raw earth and rammed earth architecture (GOLEHM, n.d.). Future research can therefore more easily compare found improvements to the material requirements of said building norms. In relation to this scope of location, all following scopes are adjusted to keep a focus on Northwestern Europe.

Function of material
To be able to provide a sustainable alternative to common high-emission construction materials (like concrete, steel, and brick) the resulting material must be structural in use. If the material cannot be used structurally, the potential implementation of the material is minimal. Additionally, the material must be able to efficiently be produced on a large scale. If material production methods can only be done manually, the resulting material is not a competitive option. For the same reason, building construction methods should be optimised, minimising time and labour.

Historic rammed earth architecture
Although the history of each raw earth construction method can be researched in depth, this research mostly aims to provide a brief description of the overall history of raw earth as a construction material and the importance of this knowledge for modern architecture. Rammed earth construction can be compared to the various raw earth construction techniques, demonstrating the advantages and disadvantages of the specific construction method. This research will furthermore focus on providing the generalised information necessary to create rammed earth structures, both in production techniques and material mixtures.

Historic bio-based binders
As historic bio-based binders are not documented well throughout history (Zeng et al, 2008), acquiring knowledge on the matter is considered challenging. Given this challenge, the research will also provide an initial overview of historic bio-based binders. A complete guide to these binders would require additional extensive research on the topic; both using historic literature archives and intensive material testing of monumental architecture.

As the initial overview of historic binders gives an incredibly large quantity of possible material variations, a selection of the discussed binders must be made before testing. This is done by formulating desired material properties and plotting these into a matrix. By equating the properties to the discussed binders, the matrix will be used to determine the most promising bio-based binders.

Implementation bio-based binders
The initial scope of the binders can be given by drawing conclusions on the overview matrix and choosing a select number to sample. Wet mixture testing will be conducted using the first selection of binders, with which a first impression of their performance can be determined. This allows to narrow down the scope of binders once more, to a limited number of promising binders. The most promising binders will be tested in their hardened states. Conclusions from the second round of testing can once more be used to narrow down the scope, determining the top performing binder. The best performing bio-based binder can then be used for prototyping, to further study the material behaviour in real-life scenarios.

To be able to conduct this testing, a raw earth mixture must be used to which the binders can be added. Due to the high variety of potential rammed earth mixtures, testing using various earth mixture would result in too many testing variables. For this reason, a locally pre-produced earth mixture is to be used. This provides consistent properties regarding the earth mixture, accounting for locally available material properties, allowing for the binders to give an accurate insight into their potential added benefits.

1.5. Research Questions
Looking at the problem statement and research objectives, the following research questions can be formulated:

Main question:
- How can the use of bio-based binders improve the material performance of rammed earth in Northwestern European building construction?

Sub questions:

1. What material property enhancements are possible for modern-day rammed earth construction?

2a. What bio-based binders have been used in historic raw earth construction?
2b. What were their intended adjustments on raw earth material properties?

3. What information from rammed earth history can be applied to the use of modern-day rammed earth?

4. How can the performance of bio-based binders in rammed earth constructions be tested?

5. Which bio-based binders can be implemented for possible material enhancement of modern-day rammed earth construction in Northwestern Europe?

6. How does the implementation of these bio-based binders in rammed earth mixtures affect rammed earth performance?

7. How do rammed earth constructions using bio-based binders perform compared to those made with the commonly used cement binder?

1.6. Outline of research

The research can be divided into four stages. The first stage; literature research, aims to answer the above-mentioned sub questions of this research.

By answering these sub questions, information is gathered to start the second phase; mixture testing. This testing is necessary to move on to the third phase; sampling. The samples produced in the third phase are used in the fourth stage; testing.

Stage 1 - Literature research

In stage 1 literature research is conducted on two main topics; historic raw earth construction techniques (with a focus on rammed earth) and historic bio-based binders. This literature research was conducted using various forms of publications and interviews. When the data on historic binders cannot be retrieved, as traditional building techniques rely on oral tradition, a broader search scope outside of the rammed earth sector is applied. Examples of this broadened scope are literature on the history of adhesives, modern binder use, and earth mortars. With the found information regarding rammed earth and bio-based binders, conclusions can be drawn. The conclusions form a hypothetical ideal rammed earth material mixture. Moreover, suitable rammed earth testing techniques are determined using literature research.

Stage 2 - Mixture testing

In stage 2 mixture testing is conducted. This testing is prepared by incorporating the most promising binders, at various percentages, into a pre-made rammed earth mixture. While creating the various mixtures, the testing will be conducted by observing the mixture consistency and texture. The optimal mixture performance is described with various rules of thumbs and practical visual tests found in related literature. This allows for a first round of conclusions on binder performance, indicating promising binder types and their potential optimal percentages.

Stage 3 - Sampling
In stage 3 samples are made to later be used for testing. Formworks of varying sizes are made to prepare for the sample construction. Dimensions of said formworks are decided according to the required sizing dictated in the considered tests. When sizing is not specified, construction industry standard test sample sizing is applied. These industry standards can be found in the testing of common construction materials like concrete or brick. Correct determination of sample sizing allows for accurate comparison to results on similar tests conducted by other researchers. Samples are constructed using the most promising binders and their potential optimal percentages found in stage 2.

Stage 4 - Testing
In stage 4 the finished samples are tested against both strength and weathering requirements. These tests are based on existing rule of thumb tests in the compressed earth construction sector as well as standardised strength testing of materials. In this way, both visual cues of performance and quantitative values of performance can be attributed to the samples. Using the rules of thumbs allows for sample comparison against standard rammed earth construction. Using the traditional strength testing of materials allows for sample comparison against alternative materials, like stabilised rammed earth or concrete. To ensure validity of these tests, several samples of each earth mixture will be tested. This allows for statistical validation of test outcomes.

2. Literature

2.1. Raw Earth Architecture

2.1.1. Introduction raw earth architecture
Raw earth has been used as a construction material since the beginning of dwelling usage (Birznieks, 2013). Additionally, raw earth was used for impressive feats of architecture like temples or entire cities (Ganotopoulou, 2014). The material can be found in each geographical context: in nearly all climates, in all environments, be it mountains or plains, and on every continent (Dethier, 2020). To compensate for this highly varying material, local know-how was imperative (Norton, 1997). As Lubelli (2018, p.55) states

"Rather than the product of the creative genius of a single person, these [raw earth] buildings are the 'collective' result of knowledge of techniques and materials acquired during centuries of experience and transmitted via generations of craftsmen".

Through the Industrial Revolution the use of raw earth materials has however lost popularity (Marsh, A. & Kulshreshtha, Y., 2021). Still, a large part of the world´s population lives in dwellings made from raw earth. The exact amount is to be debated, due to the unregistered use of raw earth architecture in developing countries (Birznieks, 2013). According to Gantopoulou (2014) the number reaches about 50%, although Birznieks (2013) gives a number of 33%, and Van Gorp (2018) gives a number as low as 25%. This is all a very significant amount, illustrating the universality of raw earth architecture.

Benefits raw earth

As Norton (1997, p. PVII) states *"Earth has many advantages as a material, not least of which is its availability"*. Besides being available anywhere on the planet, raw earth has the ability to maintain a stable indoor climate, both regarding humidity levels and temperature (Birznieks, 2013). In addition, day heat gets equally dispersed overnight. The construction with raw earth produces no volatile organic compounds (Van Gorp, 2018). Raw earth also provides a positive indoor olfactory environment by absorbing smells. Moreover, compacted earth provides for good sound insulation (Dethier, 2020).

As proven throughout time, raw earth buildings require little energy to be produced and emit few greenhouse gasses (Dethier, 2020). Stated by the NIBE environmental classifications, raw earth construction materials have one of the lowest environmental costs (Birznieks, 2013).

Architecturally, raw earth architecture allows for creative freedom. A wide array of colours and textures are available. When the natural ranges do not satisfy the desired colour or shade, pigments can be added easily (Birznieks, 2013).

Also socially raw earth use is known to have benefits. The use of raw earth as a material, with its corresponding construction techniques, promotes a worldwide diversity of cultural identities. Implementing cultural knowledge on construction revives tangible and intangible values, vernacular thinking, and communal education. This attention to local craftmanship can aid in restoring the lost dignity and pride in using traditional materials and construction techniques. Due to its characteristically local production, it also practically benefits local communities by providing employment (Dethier, 2020).

Drawbacks raw earth

Due to the capillary action in raw earth, constructions in humid climates need to be built on a base made out of alternative, non-capillary, materials. Without the use of stabilisers, the compressive strength of raw earth is minimal, restricting the potential construction hight (Norton, 1997) (Dethier, 2020). Additionally, this causes raw earth architecture to be vulnerable to natural disasters and extreme weather conditions (Norton, 1997).

Socially, the use of traditional materials can cause inhabitants of earth dwellings to feel like they are in psychological and cultural regress, reverting to the past instead of evolving to the future (Dethier, 2020) (Marsh, A. & Kulshreshtha, Y., 2021).

2.1.2. Raw earth construction techniques

To be able to make an inventory of the various raw earth construction techniques, this research will make use of the 'Wheel of Techniques', developed by CRAterre. Founded in 1979, CRAterre is the international centre for Earthen Architecture. They aim to gain recognition for earth materials as sustainable and circular options for modern construction, while preserving cultural and heritage knowledge on the matter (CRAterre, n.d.). As such, their framework described in the 'Wheel of Techniques' (CRAterre, 1994), first published in 1989, has become an industry standard of describing raw earth construction techniques (Dethier, 2020). See figure 1.

A short explanation of each raw earth construction technique is provided in *appendix 1: Description earthen construction techniques.*

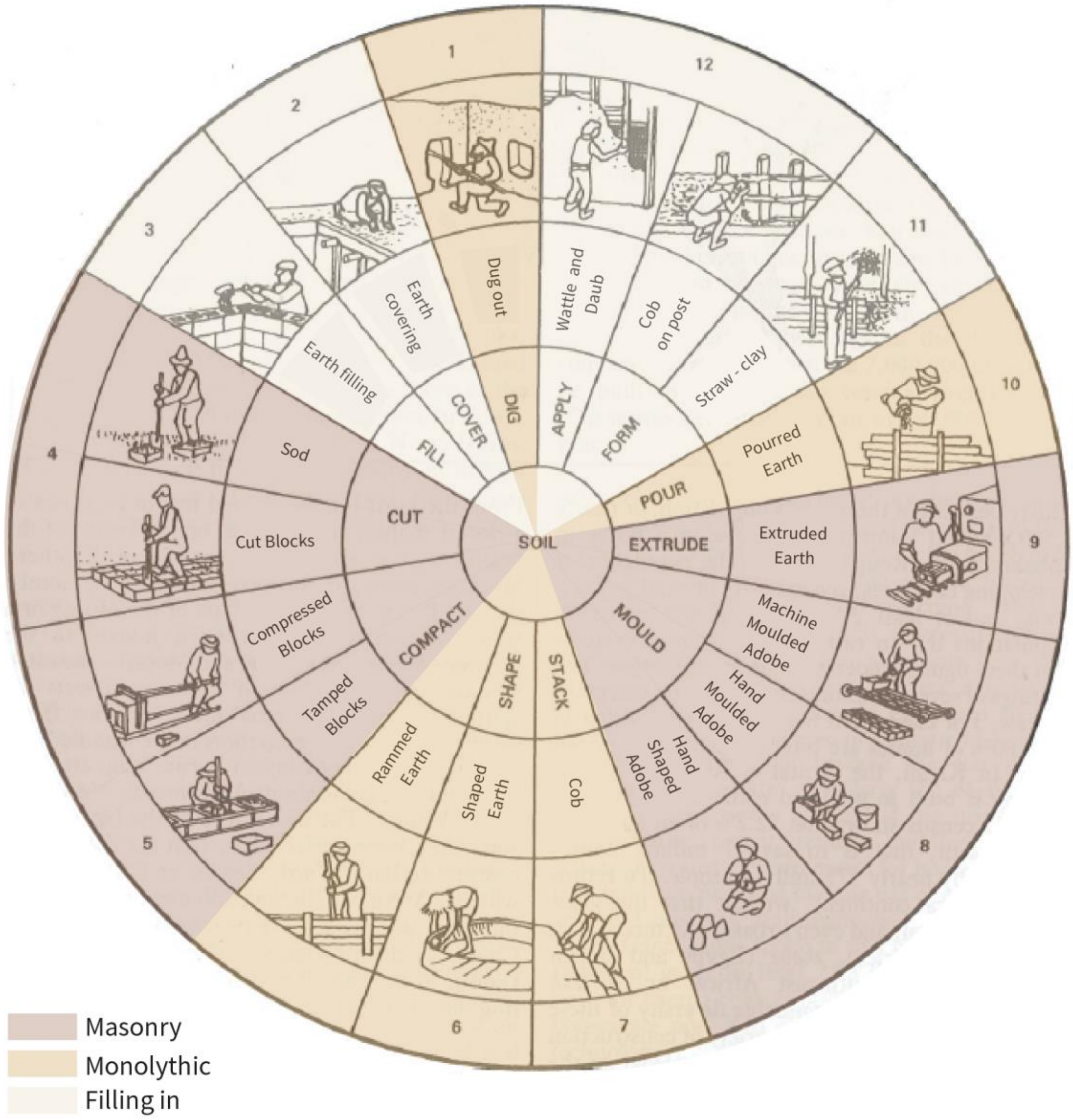


Fig. 1 - Wheel of Techniques – Adapted from CRATerre, 1994
(Grunacker, 2021)

All the construction techniques mentioned in the wheel make use of earth, thus all benefiting from the sustainable characteristics of the material. However, this research is attempting to find a material that can be implemented in Northwestern Europe as an alternative to the commonly used building materials, which are high in energy consumption and emission production (Zuiderveen et al, 2023). The material should additionally be straightforward to implement during the design and construction of a building, to compete with the industry standard construction methods. Translating these demands on the desired research outcome into scopes, leads to the following:

- Location
- Function
- Production
- Construction

To be able to draw conclusions from the formulated scopes, they are applied to the '*Wheel of Techniques*' in the following chapter.

2.1.3. Suitable raw earth construction technique

To determine the most suitable technique to achieve the research objective, the scopes can be projected onto an overview of raw earth construction techniques. By doing so, an elimination process is created. This elimination process eventually leads to the earthen construction material most suitable for being a potential sustainable alternative to contemporary building materials. The 1994 CRATerre '*Wheel of Techniques*', *figure 1*, will serve as an overview of raw earth construction techniques for structuring this elimination process. The numbers on the wheel, correlating to each raw earth construction technique, will be used in this chapter when referring to construction techniques.

Location

The relevant areas of consideration can be determined using the research scope regarding location, Northwestern Europe, resulting in the following countries (RVO, 2024) (Climate ADAPT, n.d.). The most implemented raw earth construction techniques *(see Chapter 2.1.2.)* for the defined areas are as followed (Dethier, 2020) (Correia et al., 2011):

Region or Country	2. Cover	4. Cut	5. Compact	7. Stack	8. Mould	11. Form	12. Apply
Benelux	- Earth covering			- Cob			- Wattle & daub
Germany			- Tamped blocks	- Cob	- Hand shaped adobe - Hand moulded adobe	- Straw clay	- Wattle & daub
France			- Compressed blocks - Rammed earth	- Cob	- Hand shaped adobe		- Wattle & daub
Scandinavia	- Earth covering	- Sod	- Rammed earth	- Cob	- Hand moulded adobe		
UK & Ireland		- Sod		- Cob	- Hand moulded adobe		- Wattle & daub - Cob on post

Table 1 – earthen construction techniques found per location

From this overview, it can be noted that not all 12 raw earth construction techniques described in the '*Wheel of Techniques*' can traditionally be found in Northwestern Europe. The 7 remaining techniques are:

2. Cover
4. Cut
5. Compact
7. Stack
8. Mould
11. Form
12. Apply

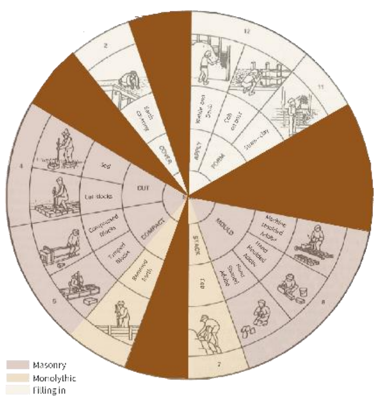


Fig. 2 - Wheel of Techniques – Location

Brief historic summaries of Northern European raw earth construction techniques are provided in *appendix 1: Description earthen construction techniques*, at their dedicated overview.

Function

The second research scope to be applied for the elimination of techniques is the chosen material use. The materials used in the built environment that produce most harmful emissions are mostly observed fulfilling a role in the building's structure (Zuiderveen et al, 2023) This means the 'ideal' earthen construction technique must be able to be used structurally, in a load-bearing manner, to be able to optimise emission reduction caused by the built environment. According to Norton (1997) and Houben & Guillaud (1994) the following 3 raw earth construction techniques can be load-bearing in use:

5. Compact   7. Stack   8. Mould

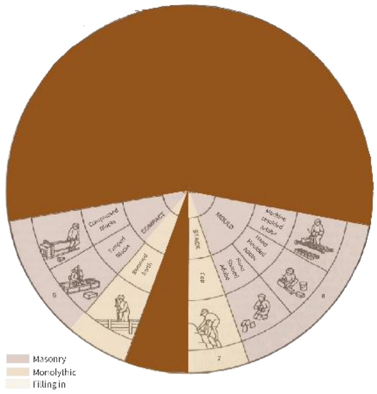


Fig. 3 - Wheel of Techniques – Function

Production

A modern obstacle raw earth construction faces is the penetration of the material lobby, attempting the implementation of the material while having to adhere to unsuitable building regulations (Dethier, 2020).

To ensure the chosen construction technique can readily be implemented in the modern built environment, thus functioning as a valid material alternative, the raw earth technique should be able to be produced on a large scale. One of the ways production can be scaled-up is by creating a ready-to-use building product. This additionally guarantees product standardisation, allowing the material to fit building norms and regulations.

The production standardisation is necessary because under laboratory conditions, the material still cannot pass mechanical performance and durability tests common in the construction industry (Dethier, 2020). The construction techniques suitable for production standardisation are (Minke, 2006):

5. Compact   8. Moulded adobe

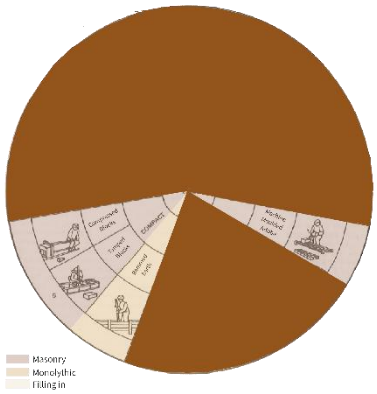


Fig. 4 - Wheel of Techniques – Production

Construction

The fourth and final research scope to be applied is related to ease of construction on site, limiting the necessary project time. A limited project time will make the material more cost effective, thus more appealing (Birznieks, 2013). Both construction methods to be considered resemble common construction materials. Compacted earth resembles concrete elements. Moulded adobe resembles fired bricks (Minke, 2000). When comparing concrete elements to fired bricks, larger concrete panels allow for heightened quality control, quick construction times, and reduced labour costs (Ni et al., 2021). To emulate these same characteristics in raw earth materials, large pre-fabricated elements are necessary. This makes pre-fabricated rammed earth the most suitable raw earth construction method for achieving the research objectives.

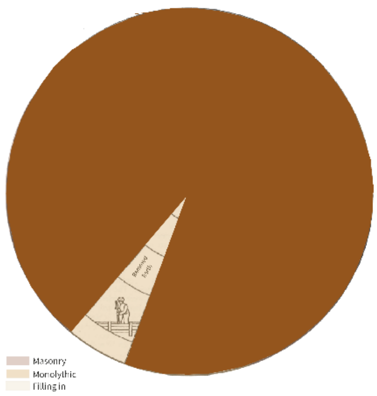


Fig. 5 - Wheel of Techniques – Construction

5. Compact: pre-fabricated rammed earth.

2.2. Rammed Earth Construction

2.2.1. Introduction rammed earth architecture

Rammed earth describes both a material (a moist mixture of sand, clay, silt, aggregates, and potential binders) and a construction technique in which the materials is compacted in layers in a (re)movable formwork. Compaction is achieved with the use of so-called rammers: the tools that exude the necessary force onto the mixture. After removing the formwork, the built structures are left to dry until hardened. The resulting product is an in-situ, monolithic, self-supporting, construction (Birznieks, 2013) (Norton, 1997) (Houben & Guillaud, 1994).

The construction method of rammed earth is similar to that of Compressed Earth Blocks (CEB), the main difference being the scale of the end product (Ganotopoulou, 2014). Other terms to describe this same construction method are Pisé (de terre) in French, Stampflehm or Lehmbau in German, Tapial in Spanish, and Taipa in Portuguese (Ganotopoulou, 2014) (GOLEHM, n.d.).

Although rammed earth is a construction method and material used worldwide throughout history, over the last 35 years an attempt has been made to modernise rammed earth construction with the use of academic testing and field experiments. This testing is focussed on the construction process and detailed soil analyses (Dethier, 2020). This allows for the material to now be mechanically mass-produced off-site into pre-fabricated panels by construction companies (Ganotopoulou, 2014), such as the factory of LehmTonErde (Rauch, 2020).

Research from the university of Bath revealed that for cold and wet climates, as is the case in Northwestern Europe (Boudrea et al., 2023), rammed earth buildings should be small-scaled with added insulation. The researchers also stated that preferably as little rammed earth is exposed to the outdoors (Maniatidis, Walker, 2003). Rammed earth can not only be used for facade construction, but it can also be made into interior walls, floors, stairs, and even furniture (Gunnarsdóttir, 2021).

While raw earth already is one of the most sustainable building materials (Birznieks, 2013), rammed earth is in the top of earthen construction techniques regarding sustainability, providing promising potential uses in modern architecture (Rauch, 2020). To further compare the use of rammed earth to other earth construction techniques, the following is a summary of specifically rammed earth construction benefits and drawbacks for construction in Northwestern Europe.

Benefits rammed earth

- High thermal mass (Ganotopoulou, 2014)
- Self-supporting, load-bearing structures (Norton, 1997)
- Allows for several stories in a construction (Dethier, 2020)
- Most sustainable raw earth construction technique (Rauch, 2020)
- Improved sound absorption and air-borne sound reduction (Birznieks, 2013)
- Fire resistant due to the lack of incorporated combustible materials (Ganotopoulou, 2014)
- Breathable and vapour permeable when not stabilised with inorganic materials (Norton, 1997)
- Walls can be left untreated, providing a characteristic architectural style (Dethier, 2020)

Drawbacks rammed earth

- Sensitive to frost damage (Houben & Guillaud, 1994)
- Sensitive to water damage (Houben & Guillaud, 1994)
- Poor thermal insulation qualities (Norton, 1997)
- Does not meet building norm required compressive strength without additional inorganic stabilisers (Van Gorp, 2018)
- In-situ construction requires soil workability, manpower, and is time consuming (Dethier, 2020)
- In-situ construction method requires cooperative weather conditions (Ganotopoulou, 2014)
- Prefab construction method increases embodied energy of structure (Ganotopoulou, 2014)

2.2.2. Historic rammed earth architecture

The rammed earth technique is known world over, but the material development through history is sparsely documented. The material seems to repeatedly gain popularity, during periods with needs out of the construction sector norms, only to fall out of favour again (Jaquin et al., 2008). Although the widespread nature of the technique, this research will solely discuss the history of European rammed earth architecture, with a focus on Northwestern Europe. The assumption can be made that in the areas where monumental rammed earth architecture can be found, vernacular rammed earth architecture was also present (Jaquin et al., 2008).

Ancient history

Experts concur that European rammed earth was invented by the Punic civilization of Carthage, existing between 650 BCE to 146 BCE (Dethier, 2020), around the Mediterranean (Jaquin et al., 2008). Evidence of Carthan rammed earth buildings can be found in Spain, Morro de Mequitilla (Jaquin et al., 2008). Through interactions between Carthage and the Romans, rammed earth was brought to Europe in Italy, and France (Dethier, 2020). Pliny the Elder writes about general Hannibal of the Carthaginians constructing rammed earth towers (Jaquin & Augarde, 2012).

Although the Romans preferred concrete with pozzolanic, proof of rammed earth construction can be found throughout the Roman Empire (Van Gorp, 2018). In Vitruvius´ publication '*De architectura*', 23 BC, all Roman construction techniques can be found. This includes descriptions of rammed earth construction in Marseilles, France (Jaquin et al., 2008). Further proof of Roman rammed earth construction is found in archaeological excavations in several parts of Southern France (Houben & Guillaud, 1994). The French word for rammed earth, *pisé*, can also be directly linked to the Romans. Derived from the Latin word *pinsere,* translated to 'the action of ramming earth' (Jaquin et al., 2008).

In Spain, rammed earth was further developed during the Berber dynasties of the Almoravids (11th - 12th centuries CE) and the Almohads (12th-13th centuries CE), resulting in impressive buildings like the Alhambra in Granada (13th-14th centuries CE) (Dethier, 2020).

Seventeenth century

It is assumed that historic rammed earth constructions were common in Christian medieval France. This believe is based on the fact that rammed earth knowledge is shown to spread from Lyon, France, to Switzerland around 1660. An example of this newfound knowledge is the Hauptwil castle built 1665 in Geneva, Switzerland (Jaquin et al., 2008).

Eighteenth century

Beginning of the 18th century, a group of craftsmen made their way through Scandinavia, constructing buildings made of compressed lime mortar and pebble-and-stone slag in removable formworks, similar to rammed earth. Their journey aimed to serve the rising demand of construction alternatives to wood, as a result of a culturally spread worry about deforestation in Europe (Jaquin et al., 2008).

This concern of deforestation, in combination with social unrest, resulted in the demand of the appreciation of the common worker, causing revolutions Europe wide. Rammed earth was coined as the construction method of the common worker: self-made and low-cost. In France between 1770 and 1790, several articles on the topic of rammed earth were published in this context. None, however, as successful as the series of François Cointeraux in 1791 (Jaquin et al., 2008). This publication coincided with the turmoil of the French Revolution of 1789-1799 (Gramlich, 2013).

Cointereaux introduced nouveau pisé and with it, his views on modern rammed earth construction. In these books, he describes his philosophy on making no distinction between towns and the countryside. He argues land management should "take into account the biological and geographical features of its ecosystem.". He also puts an emphasis on water not just being detrimental to raw earth, but rather being a fundamental component of raw earth architecture (Dethier, 2020). He repeats the idea of rammed earth as the material for the common man. This gained ground in the French Revolutionary committees, transforming rammed earth into a symbol for freedom from oppression (Gramlich, 2013). Cointereaux states the following (Doat et al., 1991):

" (…) travelling along the banks of the Saône (…) they never dreamt on seeing these elegant, these delightful, country houses that were built solely with earth. (…) Allow me to observe that this building method should be employed all over the country, both to enhance our villages and our national honour, and to save the wood that is used in such large quantities for building (…). The material can later be used as an effective fertiliser (…)."

In the French region of Auvergne-Rhône-Alpes, and cities of Lyon, Carpentras, Narbonne, Béziers, and Perpignan, examples of rammed earth, or archaeological evidence of its use, from Cointereaux's time period can be found. Many of these buildings are still currently in use. Some of these buildings at the Croix-Rousse in Lyons, Cointereaux's birthplace, even reach six storeys. Knowledge on these constructions and methods, like knowing 'good earth' from 'bad earth', was however not recorded but passed down from master to apprentice (Dethier, 2020). What is recorded, is that these walls were constructed using small wooden forms, moved along the length of the wall to reach desired length. The width averages at 40-60 centimetres (GOLEHM, n.d.).

In Denmark, 1796, Klaus Henrik Seidelin published a translation of Cointereaux's '*École d'Architecture Rurale*'. In 1798 his work was in turn translated and brought to the Finnish market. The vision of this literature spread from Scandinavia to Russia. In 1798 Tsar Paul I commissioned the Barracks in Torzhok, existing of earth walls and a thatched roof. L'vov, the architect, convinced the Tsar of the advantages of rammed earth. He wrote "[that it] was ideal in regions devoid of timber and [its use] could also solve the problem of the preservation of the forests throughout Russia.". As a result, the Tsar allowed L'vov to establish two Schools of Earth Construction near Moscow (Gramlich, 2013).

The popularity of Cointereaux's works was also noticed in the rest of Europe. In England Henry Holland published parts of this works in 1797. Although Holland was not alone in translating these works, his publication is widely known because it resulted in the spread of rammed earth to other Anglophone countries like Australia, New Zealand, and North America (Gramlich, 2013). In 1798, Guiseppe del Rosso published a translation in Italian (Jaquin et al., 2008).

Following the French Revolution there was a succession of wars: the 1803-1815 Napoleonic Wars. As a consequence, Europeans suffered a total period of twenty-five-year of general shortages. This further drove the development of rammed earth popularity to construct using limited resources (Gramlich, 2013).

Nineteenth century

The hugely popular translations of Cointereaux's work resulted in a rammed earth boom all over Europe. Although cob remained the main earth construction method in England, rammed earth villages were constructed around 1830 at the southern coast. In Germany, the height of this boom can be found around 1840 (Ganotopoulou, 2014). As a clear example, by 1871, over 4,000 houses were built in Denmark on the nouveau pisé principles (Gramlich, 2013).

Inspired by nouveau pisé, David Gilly, the German 'Master Builder', released a publication in 1828 detailing rammed earth construction and highlighting the importance of agricultural architecture. One of his founding arguments was the reduction of wood use. This drove the Prussian administration to subsidise rammed earth construction at the end of the eighteenth century (Fissabre & Wilson, 2012).

The English William Wilds published a book in 1835 to inform the people emigrating from England to other continents, as a result of overpopulation post Napoleonic Wars and the economical state of the country, on nouveau pisé. His aim was to implement rammed earth for them to cheaply and quickly construct their new homes abroad (Gramlich, 2013).

In Germany, Wilhelm Jacob Wimpf taught himself the principles of nouveau pisé resulting in a book in 1836, in which he brings forward the common wasteful usage of energy and materials in the built environment. He states: "Building houses of brick is truly a sinful waste of expensive burning material and high costs.". Again, the persisting wood shortage is mentioned in favour of earth construction (Gramlich, 2013). Additionally, Wimpf is responsible for the well-known rammed earth houses in Weilburg. One of which his own home on the Hainallee 1, becoming famous for being the tallest un-stabilised rammed earth building in modern times, reaching 7 stories (Dethier, 2020).

Twentieth century

Although rammed earth construction can be found all throughout the 20th century, the construction technique was never the mainstream building method.

Following World War I, in 1914-1918, the Welsh Clough Williams-Ellis 'discovered' buildings made of earth, while inspecting the damaged plasters on historic cottages, and finding constructions using traditional earthen techniques (Jaquin et al., 2008). In 1919, he wrote a publication on earth construction, inspired by the housing shortage in England. The shortages of the time now included not only wood but also coal and quicklime, necessary for cement and brick production (Gramlich, 2013). Earth was introduced as a building material not reliant on coal (Fissabre & Wilson, 2012).

Due to high demand, a second edition of Williams-Ellis's writings was published in 1920, attributing the book's success to the popularity of rammed earth as a social construction method (Gramlich, 2013). As a result, experimental rammed earth constructions were built in England around this time period (Jaquin, Augarde, 2012). In contrast with this practical movement, the Building Research Board for the Committee of the Privy Council for Scientific and Industrial Research in England, published a report in 1922 calling the consideration of construction using rammed earth 'naïve' and deemed the technique 'insufficient' (Gramlich, 2013).

At this same time in Sweden, post World War I, earthen architecture was once again gaining popularity to combat material shortages, saving timber and iron for the ship building industry. This was done using translations of previous publications on the matter. And as was seen in the 18^{th} century, craftsmen were traveling through Scandinavia to construct these new rammed earth dwellings (Correia et al., 2011).

Once again, Europe was at war, this time being World War II from 1939 to 1945. This called for extensive re-construction plans of necessary dwellings, both during and after the war, while dealing with material shortages. On account of this, raw earth was found as a solution, being widely available even during wars (Dethier, 2020).

Albert Speer, a high ranked member of the Nazi party, even promoted the use of raw earth, stating that concrete and steel were required by the war and thus should be avoided for building construction. To implement the use of raw earth, the material got regulated in 1944, for the first time worldwide (Houben and Guillaud 1994). The promotion of knowledge on the topic of raw earth architecture furthermore allowed for reconstruction efforts after the war to also favour the use of raw earth. Whole villages were rebuilt using earth as a material (Dethier, 2022). In this time period in Germany, fired lime mortar strips were an innovation in rammed earth architecture, being used in between layers of earth for improved structural qualities (GOLEHM, n.d.).

Post war, The English Williams-Ellis published a third edition of his book in 1947, now discussing the effects of the Second World War, instead of the First (Gramlich, 2013). Even the big French architect Le Corbusier utilised raw earth and published books during and after the war, one of which '*Les constructions Murondins*' (Fissabre & Wilson, 2012). In which, he considers and illustrates the basic principles of building with rammed earth and adobe, and advocates their use for public architecture (Dethier, 2020).

The reconstruction efforts in Germany in 1946 resulted in the *´Lehmbauberatungsstelle´* (earth building advisory office) in Nienburg / Weser. Its director, Richard Niemeyer, published an official government affiliated practical manual for construction using earth (Fissabre & Wilson, 2012). The use of rammed earth after the second world war was most common in the Soviet occupation zone, later called GDR (Rath, 2004). Pollack and Richter, German engineers, published an appeal in 1952 to keep developing the use of raw earth for construction, even after the rebuilding efforts finished (Dethier, 2020).

Though all described wars saw a significant increase in the use and experimentation of rammed earth, the loss of population made the reconstruction effort impossible with the labour-intensive character of rammed earth. Thus, once again losing popularity to industrialized products like steel, fired bricks, and concrete (Joffroy et al., 2020). Alas, the last German earth buildings are observed in the 1950's (GOLEHM, n.d.).

After 1965, European countries obligated their men to either military service or civilian aid aimed at building a 'Nord-South dialogue'. Some of these men discovered raw earth building techniques in these foreign countries and brought their philosophies back to Europe (Dethier, 2020).

Upon their returns in the 1970's, these men developed new, modern knowledge on raw earth architecture, noticeably so in France, through organisations as CRAterre and public housing like Domain de la Terre (Correia et al., 2011). Compared to the expressed interest in rammed earth in 1950-1960, the organisations of the 1970's have a stronger focus on the politics behind alternative construction methods. In doing so, expressing socio-economic views on the energy demand of the built environment and expressing interest in architecture preserving local identities (Joffroy et al., 2020). This was symptomatic of a loss of faith in the Western view of economic progress (Fissabre & Wilson, 2012).

Twenty-first century

The renewed knowledge acquired by eco-conscience people of the 70's evolved into modern use of raw earth as a material for Earthship-architecture (Jaquin et al., 2008), developed by architect Michael Reynolds in the late 20th century to early 21st century. Parallel, Danish architects experimented with Earthships (Jaquin et al., 2008).

In 2000, Reynolds built the first residential Earthship in Boingt, Belgium, but was shut down by local governments. The first Earthship in Europe to receive official planning permission approval to be used as a home, was built in Ger, France, also by Mike Reynolds in 2007 (Wikipedia, n.d.).

Although several organisations were founded to further develop raw earth architecture, with the Earthship movement as a result, the material was once again abandoned for common construction use. This refusal of earthen architecture is mostly based on socio-economic factors (Doat et al., 1991). The Earthship movement did however allow for raw earth materials to be re-discovered by modern architecture (Dethier, 2022). Once again, rammed earth is considered as a sustainable and environmentally friendly building technique. The modern rammed earth renaissance is mostly based in Western Australia and the southwest United States, using cement stabilised rammed earth. Europe is currently following this trend (Jaquin et al., 2008). The frequent use of cement for modern rammed earth stabilisation is due to the lack of suitable building norms (Joffroy et al., 2020). However, research continues in search of material 'honesty' - the pure expression of the sustainable material potential, as Fissabre and Wilson (2012) express: "The material is sublimed, and symbolic: a poetics of earth as life.".

2.2.3. Contemporary rammed earth architecture

Rammed earth can be found all over Northwestern Europe (Dethier, 2020), however, in all European countries, the ease of use of industrialised construction materials resulted in the loss of rammed earth as a common construction technique (Correia et al., 2011).

As can be seen throughout the historic overview, rammed earth is time and time again considered during and after times of largescale changes to society, such as wars or severe scarcities (Correia et al., 2011). Social ideologies are often formed as a response to these changes to society. Earthen construction was always, and still is, linked to these ideologies regarding material- and social sustainability (Fissabre & Wilson, 2012). For example, further reprints of Williams-Ellis' publication generally coincide with times of economic stress or resource limitation (Gramlich, 2013).

Parallels between the historic rammed earth revival periods and current day rammed earth can be drawn: once again there is a need to construct using limited resources. Previously needed due to material scarcity, the current day need is a reduction in energy consumption and harmful emissions (Rath, 2004). Contemporary initiatives for the reinvention of rammed earth construction are unfortunately held-up by available building codes and norms, developed with industrial building products in mind. This drives construction to implement industrially stabilized rammed earth, to the detriment of the sustainable character of the building material (Joffroy et al., 2020).

Even more so, the heritage of un-stabilised earth buildings remains important. The survival of historic rammed earth constructions, remaining intact throughout time, is evidence of rammed earth's sustainable and durable potential (Jaquin et al., 2008). Continued research into historic as well as contemporary rammed earth, both stabilised and un-stabilised, is vital. Additionally to this research, an effort should be made to form two separate European building norms: one for stabilised rammed earth and one for un-stabilised rammed earth. This would allow for more sustainable rammed earth implementations in future architecture (Fabbri & Morel, 2016).

Vernacularity of architecture can additionally be considered a form of sustainability (Dethier, 2000). For example, in the GDR, similar to today, the construction of earthen architecture was considered a last measure, though those very building techniques provided housing when they were needed most, while other construction methods were unavailable (Rath, 2004). The tradition of earth building can instead symbolise the knowledge, know-how and way of living of its surrounding (Fissabre & Wilson, 2012).

2.2.4. Rammed earth mixture

A correct earth mixture is essential for the quality of rammed earth construction; if the mix is not right, cracks may form, even months after construction is finished (Eyeson, 2022). Rammed earth mixtures contain in essence; sand, clay and/or silt, aggregates, and water. The recommended proportions of each component varies by author; Eyeson (2022) recommends using 20% to 30% clay and evidently 70% to 80% sand. Maniatidis and Walker (2003) recommend using a minimum of 50% sand and no more than 25% clay or silt.

Using more than 30% clay or silt may sound efficient, as these hold the sand particles together, however in reality this will cause the construction to shrink rapidly while drying and therefore cracks appear (Ganotopoulou, 2014). Coastal sands cannot be used due to the high salt content (Ganotopoulou, 2014). Water is necessary for pliability of the mixture, but the water content should not exceed 10% (Houben & Guillaud, 1994). A higher water content causes shrinkage in the hardening process (Van Gorp, 2018).

Another essential factor to a successful mixture is the particle and grain size of the material; gravel requires a size of 2-20 millimetres, sand requires 0.06-0.06 millimetres, silt and clay require up to 0.002 millimetres (Birznieks, 2013). The range of dimensions are relevant to facilitate particle stacking; the empty spaces between larger grains are filled with the smaller particles in the mixture. Furthermore, the texture type of the ingredients is important; rough particles facilitate more friction, thus creating a stronger mixture (Dethier, 2020). Usually, rocks or pebbles are used as aggregate, however, alternatives are observed. In Germanny, the use of broken roof tiles or alternative construction rubble as large aggregate was common (GOLEHM, n.d.)

Optimum mixture strength can be achieved by letting the wet material rest before use, for a period of 12 to 48 hours (Birznieks, 2013).

Different from mass produced building materials, earth is an unaltered natural resource and greatly varies from source to source. Each soil comes with its own benefits and drawbacks (Houben & Guillaud, 1994). It is imperative to make sure the material source is not contaminated with organic matter, as this would cause the structure to degrade (Norton, 1997).

Additives

Additives are all components in a rammed earth mixture that are not crucial for construction; these materials are added to change the basic material properties of the mixture. Additives can fulfil the role of for example stabilisers, binders, colorants, or hydrophobic materials (Norton, 1997). Common stabilisers for modern rammed earth mixture are industrially made, for example cement and lime. These improve cohesion of the mixture, thus enhancing the durability and the compressive strength of the final construction (Ganotopoulou, 2014). Compared to the total mixture weight, 5-8% Portland cement is used and 3-10% lime. Bitumen can be added for waterproofing in an amount of 3-6%. Alternative additives that can be observed are soda waterglass, bio-based binders, and synthetic binders (Minke, 2009).

2.2.5. Rammed earth construction

In short, rammed earth construction consists of building a formwork, in which layers of a soil mixture get compacted using tools known as rammers. After desired construction dimensions are reached, the formwork can be removed. To reach the final product, the construction needs to hardening over a period of time (Houben & Guillaud, 1994). For a design suitable for its environment, local weathering conditions have to be taken into account (Norton, 19997).

Formwork

Constructing the formwork is the most time-consuming part of rammed earth construction, at about 50% of the total time required for the project. For most contemporary rammed earth elements, standard concrete casting formworks are used, to reduce the installation time and cost. In comparison to concrete, rammed earth can be free-standing before being hardened, thus moulds can be taken of and re-used on the next piece of wall more quickly. These moulds are held in place with ties and bolts and have a maximum height of 600 millimetres (Birznieks, 2013). This means that the formwork has to not only be moved vertically, to span the whole length of the wall, but also horizontally to reach the desired height. When prefabricated rammed earth panels are made, formworks do not have to be moved, as the product is assembled similarly to bricks. Large, hardened blocks get glued together using the same earth mixture as was used in the production of the panels (Ganotopoulou, 2014). Alternatively, one large formwork is constructed by hand to span the entire desired wall (Houben & Guillaud, 1994). Formworks must be covered in oil before use, to ensure full release after compression (Norton, 1997).

Compaction

The earth mixture gets placed in the formwork at a maximum uncompacted height of 300 millimetres (Houben & Guillaud, 1994), although heights of 150 millimetres are preferred. These layers get compacted to about 2/3 of their starting height (Ganotopoulou, 2014). The ideal energy of impact is 25 kNm/m^3 (Birznieks, 2013). By using pneumatic rammers, the construction gains a more even stratified character (Rauch, 2020). However, according to Dethier (2020) part of the charm of rammed earth architecture can be attributed to the visual imperfections hand-construction methods provide. A difference between types of pneumatic tools can be observed in two categories: impact or vibration. Both forms of compression result in similar end results, both visually and performatively (Houben & Guillaud, 1994).

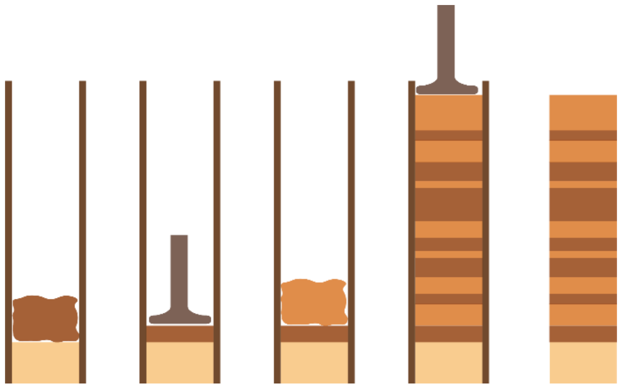


Fig. 6 - Schematic compaction process

Rammed earth walls can be constructed at a rate of 3-5 square meters per person per day, for walls of 300 millimetres thick (Birznieks, 2013). Given that structural rammed earth walls in Northwestern Europe require a width of about 600 millimetres (Ganotopoulou, 2014), this number falls to 1.5-2.5 square meters per person per day.

Hardening

The final stage in rammed earth construction is reaching a hardened state (Maravelaki-Kalaitzaki et al (2013). Structures must be dried up to 3 months for required structural qualities (Norton, 1997). However, rammed earth constructions keep gaining compressive strength and durability over their lifetime (Dethier, 2020). Following, the structure can be treated with a finishing layer, to provide weathering resistance or desired aesthetics (Birznieks, 2013).

Weathering

Rammed earth constructions left untreated will show more visual signs of weathering. The sand in the top layer, facing the outdoor environment, will get washed away over time due to rain. This gives the material a rougher appearance, revealing the aggregates within, see *figure 7* for an exaggerated example. This so called 'calculated erosion' has to be taken into account when calculating a desired wall depth. To keep erosion to a minimum, the rammed earth can be coated using plasters, oils, or paints (Minke, 2008). Alternatively, strips or tiles of weather-proof material can be placed within layers of raw earth material. This is not done out of structural necessity, but rather as a visual preference (Rauch, 2020). These weather-proof elements are called 'erosion checks' and they decrease the speed at which rain runs down walls, thus removing clay and silts from their surface (Gunnarsdóttir, 2021). Special care should be given to the detailing of raw earth corners, as sharp corners degrade much quicker. For this reason, rammed earth architecture should either be designed with rounded or chamfered corners where structural elements meet (Houben & Guillaud, 1994).

Fig. 7 - Visualisation erosion

2.3. Bio-based Binders

2.3.1. Introduction binders

Definition binder

Due to the poorly documented nature of binders in earthen constructions, various terms are used to describe ingredients crucial to the functioning of the earth mixture. In literature regarding historic earth mortars binders are defined as materials intended to improve physico-mechanical properties and durability, such as cement, lime, gypsum, and clay. Additives (adds) and admixtures (adms) are considered to be material components that are incorporated into pure earth mixtures. These 'adds' and 'adms' aim to improve various properties of earthen construction materials (workability, durability, final strength) and to reduce defects (shrinkage and long setting time) (Maravelaki-Kalaitzaki et al., 2023).

Ramesh babu & Neeraja (2017) describe the use of 'adds' and 'adms' similarly to Maravelaki-Kalaitzaki et al. (2023). However, in their research regarding concrete mixtures, they utilise the term Natural Admixtures (NAD) to describe both 'adds' and 'adms'.

Materials that can be described as 'adds, 'adms', or 'NAD' in literature when discussing other construction materials, like concrete, in fact can fulfil the function of a binder when discussing rammed earth. Therefore, when this research discusses binders, literature relating 'adds', 'adms', or 'NAD', can be used as well as research discussing binders. Bremmer (2020) describes binders related to their function in material mixture; viscous liquids or solids, able to solidify as a result of a chemical or physical reaction. This description fits both the use of inorganic binders as well as the use of the bio-based binders as intended in this research.

Inorganic binder use

Utilisation of inorganic binders can raise the compressive strength of rammed earth constructions to 18MPa, compared to a strength of 25 Mpa for common concrete structures (Birznieks, 2013). However, doing so diminishes the sustainable benefits of earthen architecture (Dethier, 2020). The frequency at which stabiliser use is chosen, in spite of the negative sustainability consequences, can be underestimated. For example, half of the nominated earth projects for the Terra Awards 2016 make use of inorganic binders (Rauch, 2020). Common cement stabilised rammed earth constructions contain up to 10% of these un-circular binders. This can be considered a problem when looking at the volume of earth, and therefore volume of stabilisers, necessary to create a wall with the same properties as that of concrete. When calculated by volume, it is entirely possible for a cement stabilised rammed earth wall to have a worse ecological performance than a concrete wall of similar dimensions (Rauch, 2020).

Bio-based binder use

Bio-based binders are seldom used in contemporary earth constructions. This can in part be explained with a lack of widespread knowledge on the topic. Another aspect to the infrequent use of bio-based binders is the total volume needed of said materials. To create enhanced material performances similar to those achieved by inorganic binders, significantly more volume of bio-based binders is needed. The increase in necessary binder drives up the total construction cost (Houben & Guillaud, 1994).

Bio-based binders are however considered crucial in the development of lime mortars, to gain mechanical properties as well as durability, that cannot be achieved in pure lime mortars. The bio-based binders can improve both the workability and longevity of mortars (Maravelaki-Kalaitzaki et al, 2023).

Focus of research

This research solely considers historically used binders, in an attempt to rediscover previously found knowledge on the topic of binders suitable for raw earth construction materials.

2.3.2. Criteria definition

To consider ‘adds’ and ‘adms’ criteria, Rampazzi et al (2016) refer to the literature of Sickels (1981) and Carbonara (2007). Maravelaki-Kalaitzaki et al. (2013) provide an overview of the required binder criteria as well. These sources record the intended actions of ‘adds’ and ‘adms’ use in mortar, which can be implemented to discuss binder use in rammed earth.

To enhance rammed earth material performance, changes can be made to the material plasticity, the material workability, the material strength, the material properties, or the drying process (Minke, 2008). The resulting relevant criteria can be sorted by the state of the rammed earth material.

Fresh state

- Increased plasticity and workability
- Increased material adhesion
- Increased or decreased viscosity
- Delayed or accelerated setting time

Hardened state

- Reduced drying shrinkage

Performance state

- Increased traction resistance
- Improved physical properties
  (porosity, thermal, water repellence)
- Improved mechanical properties
  (hardness, durability, compressive strength, tensile strength)
- Increased decay resistance to freeze-thaw cycles

Besides the criteria defined using literature, this research provides additional material criteria. These additional criteria are based on the main theme of the problem statement; the need for affordable, contemporary, low energy, low emission, recyclable building materials that can replace the common use of inorganic materials in the built environment. This allows for a reduction of the overall negative climactic impact of the built environment (Zuiderveen et al, 2023).

Criteria research aim

- Bio-based; to allow for sustainable alternative to inorganic binders (Birznieks, 2013).
- Low cost; cost efficiency allows for competitive construction use (Houben & Guillaud, 1994).
- Availability; to allow for large scale construction use, without facing material scarcity (Dethier, 2020).
- Sustainability;
  - Locally available; to allow for minimal transportation energy/emissions (Van Gorp, 2018).
  - Waste-stream; to minimise material inherent energy and emissions (Birznieks, 2013).
  - Sustainable acquisition; to reduce material acquisition energy/emissions (Minke, 2008).
  - Sustainable production; to reduce material production energy/emissions (Van Gorp, 2018).
  - Recyclability; to allow for re-use of material with minimal efforts (Birznieks, 2013).
- Material acceptance; to consider if people would welcome using the material (Dethier, 2020).

2.3.3. Matrix binders

To translate the formulated criteria into potentially promising binders for rammed earth construction, a matrix can be made. In this matrix, all considered binders are compared. The first part of this matrix gathers the known historic binders used in raw earth materials. The aim is to provide an organised overview on the general knowledge available on the binder variations, *see figure 8 - arrow 1*.

Material information

1. Material name
2. Category (*see Chapter 2.3.4. Historic binders*)
3. Historic vs contemporary use
4. Type of common use
5. Location of common use
6. Information source

To continue the matrix, the criteria previously determined according to the research aim must be added. The criteria can either be considered a '*GO – NO GO*' criteria, or a *'Negative – Neutral – Positive'* criteria. To clarify, '*GO – NO GO*' criteria need to be met to fulfil the research aim. When they are not met, the binder is eliminated from the matrix, *see figure 8 - arrow 2*. The *'Negative – Neutral – Positive'* criteria could have an influence on the overall success of the proposed material, but do not need to be met for a positive research outcome.

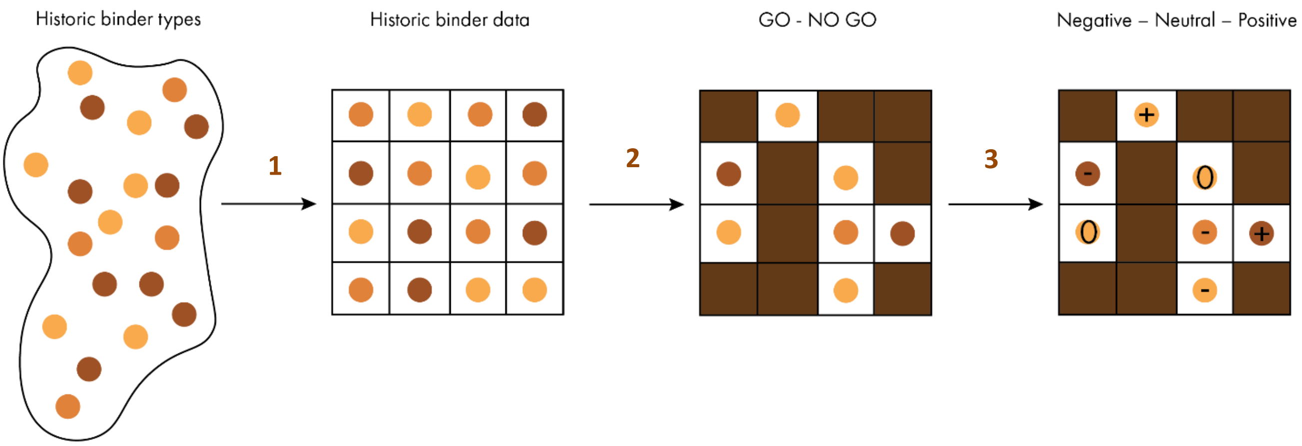


Fig. 8 - Visualisation matrix scoring

To be able to quantify the outcome of the *'Negative – Neutral – Positive'* criteria in the matrix, the category is assigned a symbolic as well as a numeric value, *see figure 8 – arrow 3 and table 2*. When a scaled value is required, *'Little – Average – Much'* is used to describe the criteria performance.

Impact on criteria	Negative / Little	Neutral / Average	Positive / Much
Impact description in matrix	-	0	+
Numeric value in matrix	-1	0	1

Table 2 – *'Negative – Neutral – Positive'* criteria translations

The numeric values found by adding the *'Negative – Neutral – Positive'* criteria to the matrix can be tallied to form a final material score: the summation of each given value per binder type. Binders with a high total score are expected to perform well in fulfilling the research aim.

Criteria research aim

7. Bio-based (GO – NO GO)
8. Low cost (GO – NO GO)
9. Availability (GO – NO GO)
10. Locally available (GO – NO GO)
11. Sustainable acquisition method (GO – NO GO)
12. Sustainable producing method (GO – NO GO)
13. Recyclability (GO – NO GO)
14. Waste-stream (-, 0, +)
15. Material acceptance (-, 0, +)

The main hurdle of contemporary rammed earth construction can be described as a lack of compressive strength when measured against the current building norms (Dethier, 2020). This indicates that a suitable binder requires a positive effect on compressive strength. In addition, perceived weaknesses for rammed earth construction in Northwestern Europe are related to ease of workability, water resistance, and resistance to freeze-thaw cycles (Minke, 2006). Resistance against these factors will be of additional benefit to rammed earth constructions.

Material properties

16. Compressive strength (GO – NO GO)
17. Plasticity and workability (-, 0, +)
18. Water repellence (-, 0, +)
19. Resistance to freeze-thaw cycles (-, 0, +)

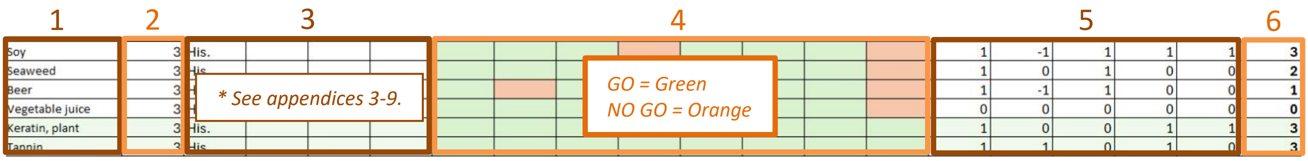
The valuation of the beneficial properties to materials, as formulated above, results in a material specific numeric value, or score. This value can be made into a new and final matrix category, the conclusion. The conclusion section will provide the most suitable binder types for this research.

Conclusion

20. Material score

Final matrix

The following image illustrates the final matrix, using the defined criteria. See *Appendix 2. Criteria matrix* for a complete overview of the resulting matrix.



1. Binder type – 2. Binder category – 3. Binder information* – 4. *'GO – NO GO'* criteria – 5. *'Negative – Neutral – Positive'* criteria – 6. Material score

2.3.4. Historic binders

The historic use of binders in raw earth construction is sparsely documented. This can in part be explained by the fact that historic binders were often materials readily available or even considered waste; not much thought went into the initial use of potential earth binders (GOLEHM, n.d.). Only through experimentation and observation over time did certain historic binders prove promising (Zeng et al, 2008).

Through history these binders often happened to be bio-based, being the predominantly available material types. Many of the historic binders can even be considered to be edible. As time passed, the use of food-based binders got discouraged; food was meant to be eaten, not used in construction (Maravelaki-Kalaitzaki et al, 2023).

The amount and type of binder necessary depended greatly on the location of construction; available resources (like local clay, sand, and binders) result in unique material mixtures at each building site. For this reason, historic binders are often strongly region specific and contain very localised knowledge (Rampazzi et al, 2016).

The historic binders this research reflects on can be organised into several categories, based on their material origin. For each category of binders, examples are found. Information is given on these examples, or potential binders, regarding their name, historic use, historic function, and location of use. Additionally, a total material score is found for each potential binder by implementing the constructed material matrix. To see the final material score for every potential binder, see *Appendix 2. Criteria matrix*. The information regarding each historic binder category can also be found as appendices. The resulting overview is a first attempt at historic binder inventory, but further research is needed for completion of the data.

1. Animal derivatives

Animal derivatives - is a category consisting of materials made by utilising parts of animal remains. Often, these parts can be considered waste streams.
Appendix 3. Historic binders - Animal derivatives.

2. Animal produced

Animal produced - is a category consisting of materials made by animals. Part of these materials are considered waste, like dung, and part are considered food, like milk or eggs.
Appendix 4. Historic binders - Animal produced.

3. Plant based

Plant based - is a category consisting of materials either derived from plants or existing of plants in their semi-unprocessed form.
Appendix 5. Historic binders - Plant based.

4. Ash

Ashes - is a category consisting of burned bio-based material. The material is burned to have the particles of the material chemically react as a result of the fire, producing new, altered particles that can create required properties.
Appendix 6. Historic binders - Ash.

5. Oils

Oils - is a category consisting of materials made of plant-based oil; the fats that can be derived from plants. Often seeds are used for oil production. Animal based oil is considered in the animal derivatives category.
Appendix 7. Historic binders - Oils.

6. Resins

Resins - is a category consisting of sugar-based secretions of various plants, mostly trees and shrubs, that harden after drying. Resin cannot be dissolved in water, additionally resins are often flammable.
Appendix 8. Historic binders - Resins.

7. Gums

Gums - is a category consisting of sugar-based secretion of various plants, mostly trees and shrubs, that harden after drying. Gum can be dissolved in water.
Appendix 9. Historic binders - Gums.

** Note: the information used to describe the categories above is a summary from all the considered literature. Sourcing for this data can be found in the related appendices.*

2.3.5. Binder choice

To be able to choose a binder, an overview of the matrix criteria scores must be given, see *Appendix 2. Criteria matrix* for the complete overview of the matrix results. The binder types that are not eliminated by implementation of the '*GO – NO GO*' criteria are sorted ranking highest to lowest, *see table 3*. Their score will illustrate their predicted effect on the material enhancement of each binder type, related to rammed earth construction in Northwestern Europe. A high score predicts a positive material outcome.

Binders meeting GO – NO GO criteria *

Name	Category	Score	Source
Plant mucilage	3. Plant based	**5**	- Maravelaki-Kalaitzaki et al, 2023 - Zeng et al, 2008 - Houben & Guillaud, 1994
Egg, white	2. Animal produced	**3**	- Ramesh Babu, Neeraja, 2017 - Maravelaki-Kalaitzaki et al, 2023 - Zeng et al, 2008
Egg, yolk	2. Animal produced	**3**	- Maravelaki-Kalaitzaki et al, 2023 - Zeng et al, 2008
Molasses	3. Plant based	**3**	- Ganotopoulou, 2014 - Houben & Guillaud, 1994
Sugar, refined	3. Plant based	**3**	- Ramesh Babu, Neeraja, 2017 - Maravelaki-Kalaitzaki et al, 2023 - Langejans et al, 2022
Keratin, plant	3. Plant based	**3**	- Maravelaki-Kalaitzaki et al, 2023
Tannin	3. Plant based	**3**	- Zeng et al, 2008 - Houben & Guillaud, 1994
Vegetable ash	4. Ash	**3**	- Ganotopoulou, 2014 - Langejans et al, 2022
Animal urine	2. Animal produced	**2 +1 = 3**	- Ganotopoulou, 2014 - Zeng et al, 2008 - Houben & Guillaud, 1994
Linseed oil	5. Oils	**2**	- Ganotopoulou, 2014 - Maravelaki-Kalaitzaki et al, 2023 - Houben & Guillaud, 1994
Rapeseed oil	5. Oils	**2**	- Lubelli, 2018
Sunflower oil	5. Oils	**2**	- Lubelli, 2018
Animal fat	1. Animal derivatives	**1 +1 = 2**	- Maravelaki-Kalaitzaki et al, 2023 - Houben & Guillaud, 1994
Animal blood	1. Animal derivatives	**1 +1 = 2**	- Van Gorp, 2018 - Ganotopoulou, 2014 - Maravelaki-Kalaitzaki et al, 2023 - Lehm people - Houben & Guillaud, 1994 - Zeng et al, 2008
Animal bone ash	4. Ash	**1 +1 = 2**	- Langejans et al, 2022

Table 3.1

** Table continues on the following page.*

Name	Category	Score	Source
Dung, cow	2. Animal produced	**1**	- Van Gorp, 2018 - Ganotopoulou, 2014 - Lehm people - Houben & Guillaud, 1994 - Dethier, 2020
Dung, horse	2. Animal produced	**1**	- Ganotopoulou, 2014 - Houben & Guillaud, 1994
Casein	2. Animal produced	**1**	- Ganotopoulou, 2014 - Maravelaki-Kalaitzaki et al, 2023 - Zeng et al, 2008 - Houben & Guillaud, 1994 - Langejans et al, 2022
Milk products	2. Animal produced	**1**	- Langejans et al, 2022
Animal glue	1. Animal derivatives	**0 +1 = 1**	- Maravelaki-Kalaitzaki et al, 2023 - Zeng et al, 2008 - Houben & Guillaud, 1994 - Langejans et al, 2022
Fish glue	1. Animal derivatives	**0 + 1 = 1**	- Langejans et al, 2022
Animal hair/fur	1. Animal derivatives	**0 +1 = 1**	- Maravelaki-Kalaitzaki et al, 2023 - Houben & Guillaud, 1994

Table 3.2 - Continuation table 3.1

Predicted suitable binders

The potential matrix scores range from positive 5 to minus 5. The highest scoring potentially suitable binder is plant mucilage, with the possible maximum score of 5. The lowest score amongst the potential binders is a 1. Keep in mind that although these scores provide a method for sorting historic binder performances, the available information on the matter is limited. It is possible that certain binders performing poorly in this criteria matrix are in fact suitable for rammed earth construction, but merely cannot be proven through available literature.

Through the scores found in the matrix, the observation can be made that five potential groups can be made amongst the highest scoring binders: plant mucilage, egg variations, molasses and refined sugar, tannins, and vegetable ash.

Although eggs and sugar products have changed little throughout history, thus staying consistent in their composition, the other high scoring binders describe concepts rather than narrowed down material compositions. This means that for example the highest scoring potential binder, plant mucilage, references the known concept of using mucilaginous plant-derivates in rammed earth construction. However, the type of plants used or necessary production methods are not described. Without the specific information per historic variation of plant mucilage, it is not possible to devise a representative material mixture. For this reason, they will not be considered for sampling in this research.

The chosen binders are therefore egg variations, sugar, and molasses.

3. Testing

To be able to draw conclusions on the impact of bio-based binders on the performance of rammed earth, testing the material is essential. The testing can give an indication of the increased (or decreased) material performance. By conducting a set of standard rammed earth tests, designed to be easy to execute, it can be determined if the material is acceptable for use in the applications required to fulfil the research aim (Minke, 2000).

3.1. Testing variables

When testing the effects of binders in rammed earth mixtures, it is imperative to test the resulting mixture both during the fresh and hardened state. At the fresh state, the sensory experiences related to the material mixtures predict the performance at the hardened sample state (Norton, 1997). After the hardened state, strength and durability testing is of the essence to determine the quantitative effect of the binder in question. This is done by comparing samples using the rammed earth mixture with and without the tested binders (Maravelaki-Kalaitzaki et al, 2023).

Besides comparing the binder samples against a control group of samples, various ratios of binders to earth mixtures have to be considered to find the optimum proportions of the mixture. According to Ramesh et al. (2017) an addition of 0,25% binders of the total mass of the earth mixture is found to be optimal. HiveEarth (n.d.) states that the maximum binder percentage is 10%. For this reason, the binder percentage is started at 0.25% and continued up until 10%, with the added percentage of 15% to ensure correct assumptions.

It is crucial to experiment with a precisely measured amount of binder, as the absence of exact standardisation in additives to earth mixtures is not only common in history but also in contemporary research on the matter (Maravelaki-Kalaitzaki et al, 2023).

The testing variables therefore are as followed:

- Binders: variations chosen through matrix implementation.
- Ratios: experimentation with percentages of binder in relation to total sampling mass.

3.2. Boundary conditions

To be able to research the influence of binders on rammed earth construction, the number of variables in the test samples has to be limited. As well as variables, time constraints are a relevant factor to drawing successful conclusions.

Soil

Because of the great variety of soils, worldwide as well as local, discussing raw earth as a general material is nearly impossible (Norton, 1997). For this reason, one of the boundary conditions of the testing is the use of a premade earth mixture. The mixture used for this research is a standard brown loam-mix, acquired from the Dutch company '*Tierrafino*'. Although the effects of the considered binders can vary with the use of different soil types and proportions, the basic principles observed in binder function are still relevant observations to rammed earth construction in general (Minke, 2008).

Sample size

As rammed earth construction requires hardening, the time passed between sampling and testing of experimentations can be a significant constraint. To avoid long drying times, smaller samples had to be made to draw initial conclusions. Future further testing can be conducted on larger samples, (dis)proving the findings of this research.

3.3. Rammed earth testing techniques

To be able to test the effect of the considered binders on rammed earth construction, samples must be made. The samples are constructed by mixing the pre-obtained mixture of earth with the chosen binders in exact ratios. Each step must be well documented to be able to draw relevant conclusions from the research.

The way the testing will be conducted can be described as three rounds; round one to determine the correct mixture composition, round 2 to check the mechanical properties of the resulting rammed earth sample, and round 3 to expose the finished samples to weathering conditions and observe their material durability.

The tests chosen for this research represent the most frequently conducted tests for raw earth samples, both adobe and rammed earth. Description of these tests can be found in all the various considered literature sources (Houben & Guillaud, 1994) (Minke, 2000) (Norton, 1997) (etc.), and are therefore assumed to be the 'industry standard' methods for rammed earth testing.

For feasibility's sake, the chosen testing methods exist out of a selection of basic tests that can be conducted without the need of laboratories. Round 1 and 3 each contain 5 tests. Round 2 however has one extra test, 6 in total, as both the abrasion and penetration test are simple and quick to conduct. The abrasion and penetration test are represented in one section. The considered 16 test methods give an extensive first impression of the effect of the potential binders on rammed earth construction.

Round 1 – Mixture composition

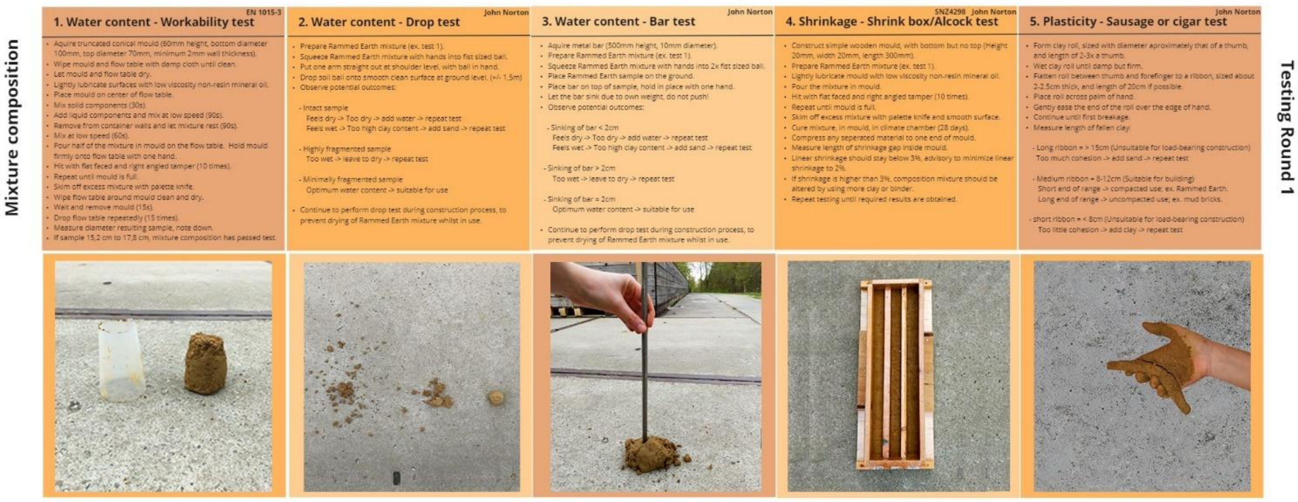


Fig. 9 - See Appendix 10. Mixture composition testing.

- Workability test (EN 1015-3)
- Drop test (Norton, 1997)
- Bar test (Norton, 1997)
- Shrink box or Alcock test (Norton, 1997)
- Sausage or Cigar test (Norton, 1997)

Round 2 – Mechanical characteristics

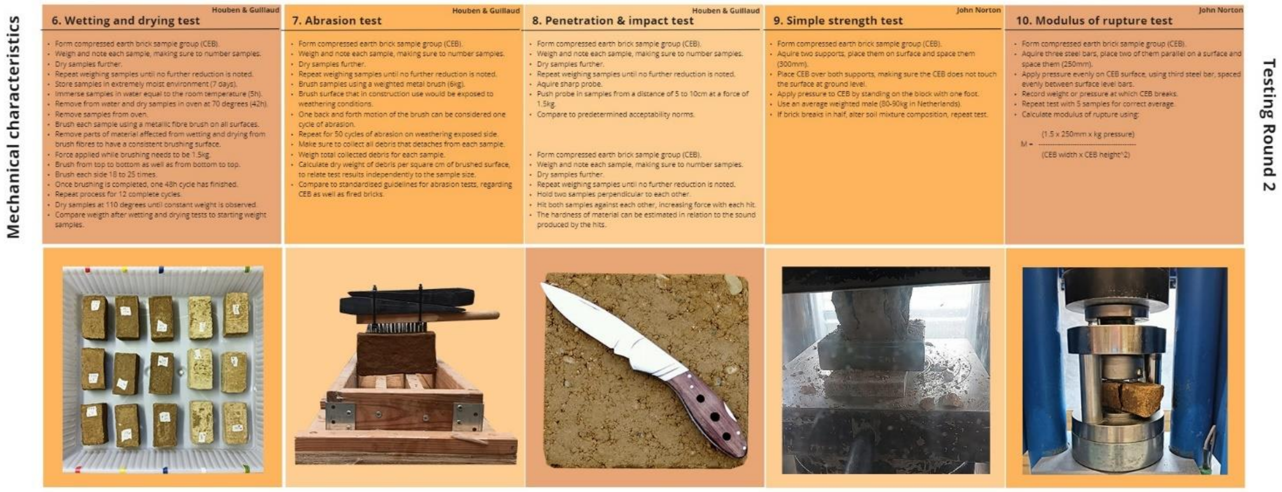


Fig. 10 - See Appendix 11. Mechanical properties testing.

- Wetting and drying test (Houben & Guillaud, 1994)
- Abrasion test (Houben & Guillaud, 1994)
- Penetration test (Houben & Guillaud, 1994)
- Impact test (Houben & Guillaud, 1994)
- Simple strength test (Norton, 1997)
- Modulus of rupture test (Norton, 1997)

Round 3 – Weathering

Fig. 11 - See Appendix 12. Weathering testing.

- Drip test (Norton, 1997)
- Spray test (Norton, 1997)
- Moisture absorption test (Norton, 1997)
- Freeze – thaw test (Houben & Guillaud, 1994)
- Outside observation

3.4. Sample construction

The samples used for the discussed testing are dimensioned according to the considered literature. The sizing of the samples naturally dictates the construction of sample formwork. To ensure layering of the material, as this is a clearly indicated potential weakness of rammed earth (Minke, 2000), a minimal height of 4 earth layers is required. To allow for consistency and precision within samples, the layer height is based on material weight, instead of material height. This means, each layer of the sample is constructed using an equal weight of the material mixture. The sizing of the samples is predetermined by the consulted literature.

Mixture composition

- Workability test (EN 1015-3) → Truncated cone, bottom diameter of 7 cm (Plant spray, dia. 7cm)
- Shrink box or Alcock test (Norton, 1997) → Formwork producing 3 samples (60 x 4 x 4 cm) *See figure 13.*

Mechanical characteristics

To provide the possibility to have a compression test of which the results can be compared to standardised information regarding concrete and brick compression test, the basic formwork is sized to be cube measuring 15x15x15 cm, *see figure 12*, as the standardised cylinder shape is complex to form out of rammed earth. These chosen dimensions of the cube emulate the standard cube sizing used in mechanical compression tests (as explained by the staff of the Microlab at Civil Engineering).

However, due to a delay in material delivery, the allotted drying time was not feasible in execution. This required smaller samples to be made, speeding up the hardening process. The existing cube formworks got sized down to resemble brick-like blocks, measuring 8x15 cm, *see figure 14*. The height of the samples is determined by making 4 layers, each weighing 500 grams. This results in a block with a weight of 2 kilograms before drying and a height of approximately 7 centimetres. This 'standard' block is used for all testing with unspecified dimensions.

- Wetting and drying test
- Penetration test
- Abrasion test
- Impact test

- Modulus of rupture test (Norton, 1997) → Formwork producing 3 samples (16 x 4 x 4 cm)
- Simple strength test (Norton, 1997) → Separated parts 'Modulus of rupture test'

Weathering

For the weathering tests, no set dimensions are given in the literature. For this reason, each weathering test makes use of the 'standard' block.

- Drip test
- Moisture absorption test
- Spray test
- Freeze and thaw test

Fig. 12 - Basic formwork

Fig. 13 - Shrink box formwork

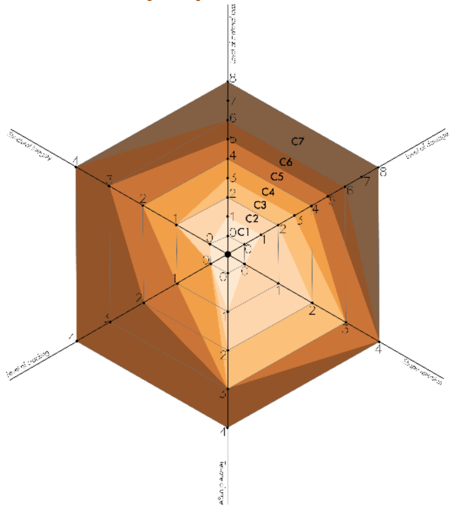
Fig. 14 - Altered formwork

4. Testing execution and results

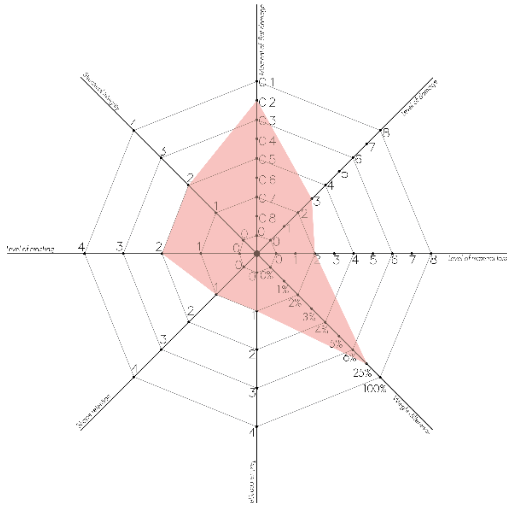
The tests conducted on the samples are based on the standardised rammed earth testing methods. However, due to the intended field nature of these tests, not all descriptions are complete nor specific. To replicate the rammed earth ‘tests of thumb’, the tests are followed as closely as possible to description in literature, within available means. Detailed descriptions of altered test methods are provided per chapter.

For interpreting the results, a system using radar charts is implemented where suitable. In this system there are two different types of charts: the multi-coloured charts, for the level of damage sustained at each time interval of a test (showing the damage progression) and the charts in red, illustrating the final damage sustained. Not all tests are detailed enough to provide data regarding damage progression.

Example process chart



Example result chart



The categories on each spoke are based on the observed changes during testing. These changes are based on the senses: sight, touch, hearing, smell. To be able to quantify the observations, sketches are added that represent the values on the spokes, see *figure 15*. This allows for a consistent & replicable assessment of results per sample type. The red radar chart, representing the damage at end of testing, includes these sensory observations as well as quantitative observations, for example weight changes, or depth of damage.

The performance of the samples will be organised by summing the values on the radar charts, resulting in a total score. A high score indicates a high level of material failure and results in a larger image on the radar chart. The resulting scores can thus be ranked for each test. The coordinating colours can be seen in *figure 16*.

Fig. 15 - Example radar chart scoring scale

Ranking	6th	5th	4th	3rd	2nd	1st
Colour						

Fig. 16 - Ranking colours

The ranking order of each test can be added together numerically per sample type. Each binder material therefor has a total accumulated score of performance. The best performing binder will have the lowest total score, indicating least amount of sustained damage. When scores are tied, moments of failure are considered additional to the total score. These total scores are however not weighted for relevance to in-situ construction of test outcomes, thus only showing the material ranking related to this research. For this reason, it is possible that in-situ construction results differ from those of this research.

4.1. Mixture composition testing

All mixture composition testing is conducted on the wet material mixture, before the drying process hardens the material. This is done to give an indication of the level of workability of the considered mixture composition (Minke, 2000). Moreover, the behaviour of the wet rammed earth mixture predicts the properties of the resulting rammed earth object (Norton, 1997), using literature-based testing (Houben & Guillaud, 1994) (Minke, 2000) (Norton, 1997).

Preparations mixture composition testing

In the matrix regarding historic binders, the most promising binders are determined. These are repeated in *table 4*. Additionally, dehydrated albumen was added to the potential binders, to negate the negative effect of added moisture while using liquid albumen. In preparation for the mixture composition tests, calculations have to be made of the desired mixture compositions. These calculations translate a percentage of the binder into an amount of gram. For this test, samples of 100 grams in total are made. The minimum binder percentage is based on the research of Ramesh et al. (2017), that concludes that the optimum binder percentage in rammed earth construction is 0.25% of the total mixture. The maximum considered binder percentage is 10%, based on the advice of HiveEarth (n.d.). An upper limit of 15% binder of the total mixture volume is added to compare to the predicted maximum percentage. An overview of the chosen binder percentages can be seen in *table 5*.

Mixture type	Binder variation
Regular	n/a
Cement	Portland
Beet sugar	Granulated & household syrup Granulated Household syrup*
Chicken egg	Yolk & albumen & shell Yolk & albumen Yolk Albumen, liquid Albumen, solid (= dehydrated)

Table 4 - Chosen binder variations

Predetermined Percentage	Weight Rammed earth	Weight Binder
0,25%	99,75 grams	0,25 grams
1,00%	99 grams	1 gram
2,00%	98 grams	2 grams
3,00%	97 grams	3 grams
4,00%	96 grams	4 grams
5,00%	95 grams	5 grams

Table 5.1 - Tested binder percentages

Predetermined Percentage	Weight Rammed earth	Weight Binder
6,00%	94 grams	6 grams
7,00%	93 grams	7 grams
8,00%	92 grams	8 grams
9,00%	91 grams	9 grams
10,00%	90 grams	10 grams
15,00%	85 grams	15 grams

Table 5.2 - Tested binder percentages

** The implementation of beet sugar molasses is based on the considered literature discussing the use of jaggery in rammed earth construction (Ramesh Babu & Neeraja, 2017). Jaggery is a sugar product based on cane sugar, including both granulated sugar and molasses. In jaggery, the molasses percentage is an average of 20% (Sankhla et al., 2011). For this reason, the combination of granulated sugar and molasses is determined at a ratio of 80% granulated sugar and 20% molasses. An additional ratio is made, using 50% of either binder. Due to a misunderstanding of the difference between molasses and syrup, in conducted tests syrup was used instead of molasses. This means no samples using molasses were conducted.*

4.1.1. Observations mixture compositions

Execution observations mixture compositions

Requirements

- Pre-made rammed earth mixture
  Note: coarse aggregates removed.
- Scale, regular
  Range: minimum 1.5kg.
  Precision: 1g.
- Scale, sensitive
  Range: minimum 0.2kg.
  Precision: 0.1g.
- Mixing containers
- Mixing utensils
- Drying set-up
  Note: samples must be able to dry at a predetermined location to avoid mix-ups.

Test process

1. Prepare calculations for considered mixture compositions.
   Note 1: see table 4 & 5.
2. Produce all mixtures with varied percentages of one binder variation.
3. Document sensory findings of mixing in writing, and where possible, visually.
4. Conduct determined mixture composition tests:
   Drop test. Shrink box test. Workability test. Bar test. Cigar test.
5. Shape and compact mixture samples into a predetermined shape.
   Note 1: for this research, blocks of 6x4x1 cm are made.
   Note 2: compact the material as much as possible.
   Note 3: strive for sharp edges and corners when possible.
6. Document sensory findings of shaping in writing, and where possible, visually.
7. Repeat for each binder variation.

Desired results

The desired result of the observation during mixture composition is documentation on the sensory changes in the material and as a result a proposed optimum binder percentage for each binder type. These observations can in part describe the effect of the considered binders on the material mixture, and predict the hardened sample performance (Norton, 1997).

Results observations mixture compositions

The results of the observations during mixture composition can best be described using imagery, the overview of each considered binder type can be seen in the illustrations below. The sample types and percentages that showed the most promising effects on material properties and material handling are determined and assigned a colour for further testing purposes, *see table 6*.

Binder type	Binder percentage	Colour
Cement	5%	White
Sugar	2%	Yellow
Sugar	5%	Blue
Albumen: liquid	5%	Red
Albumen: solid	Equivalent of 5% albumen * = 5% x ¼ = 1.25%	**Black**

Table 6 - Chosen binder percentages

** According to the producers of the dehydrated albumen, the desired liquid albumen weight can be reached by using ¼ of the desired weight in dehydrated, or solid, albumen powder.*

Findings cement

Although cement has a clear influence on the material, the perceived differences between the implemented percentages is minimal. Any percentage between the range of 2% (the first clearly perceived influence on the material) and 7% (the last percentage in which the cement does not turn the material overly brittle) seems equally viable. For this reason, the recommended percentage of 5% (HiveEarth. n.d.) is taken.

Colour	–	In smaller percentages, cement lightens the material. In higher percentages, cement turns the material grey.
Smell	–	Cement does not influence the smell of the material.
Texture	–	Cement allows the material to have a smooth surface.
Edges	–	Cement allows the material to have sharply defined edges and corners.
Adhesion	–	Cement makes the material stick less to surfaces and hands.
Pliability	–	Cement makes the material more rigid, resulting in lessened workability.
Moisture level	–	Cement turns the material dry, requiring additional moisture.

Findings beet sugar

There is no perceived difference between the influence of granulated sugar and the influence of household syrup on the material. However, the additional moisture present in syrup makes the material overly wet, reducing the workability. For this reason, syrup is not considered a viable binder. The perceived changes thus solely relate to granulated sugar. The first positive influence on the material can be perceived at 2%, while after 5% the workability of the material decreases.

Colour	–	Sugar darkens the material. A gradual change can be perceived as the implemented binder percentage increases.
Smell	–	Sugar positively influences the smell of the material, turning the smell slightly sweet.
Texture	–	Sugar allows the material to have a smooth surface in lower percentages. In higher percentages, sugar turns the surface grainy. This is partially due to the formation of sugar crystals, but also seems to be the result of a loss of fine particles.
Edges	–	Lower percentages of sugar allow for the formation of sharper edges compared to the original mixture. Higher percentages, however, result in dull and rounded edges.
Adhesion	–	Sugar makes the material tacky, resulting in sticking to surfaces and hands.
Pliability	–	Sugar has a positive effect on the pliability, increasing the workability of the material.
Moisture level	–	Sugar turns the material moist. Although no liquid is added, the resulting material is perceived wetter and has a longer drying time. This increases per percentage.

Findings chicken egg

There is no perceived positive influence on the material by implementing egg yolk as a binder. Moreover, the use of egg yolk has a significant negative effect on the smell of the material. This same smell can be noticed when using whole eggs. The use of ground eggshell does not seem to negatively impact the material, thus could be left in when using whole eggs. Although there is a perceived positive effect on the material while using a mixture of egg yolk and egg albumen, this improvement is lower than the perceived improvement by implementing only albumen. For this reason, albumen is considered as the most viable binder.

Colour	–	Albumen darkens the material. A gradual change can be perceived as the implemented binder percentage increases.
Smell	–	Albumen has a slight negative impact on the smell of the material.
Texture	–	Albumen allows for a smooth surface of the samples.
Edges	–	Albumen allows for sharp, well-defined edges and corners on the samples.
Adhesion	–	Liquid albumen makes the material tacky, resulting in sticking to surfaces and hands. Solid albumen makes the material stick less to surfaces and hands.
Pliability	–	Albumen makes the material more pliable, increasing the workability of the material.
Moisture level	–	Liquid albumen makes the material too wet. Solid albumen turns the material dry, requiring additional moisture.

Cement

Cement – Portland cement

Beet sugar

Beet sugar – Granulated & household syrup – 80/20

Beet sugar – Granulated & household syrup – 50/50

Beet sugar – Granulated

Beet sugar – Household syrup

Chicken egg

Chicken egg – Yolk & albumen

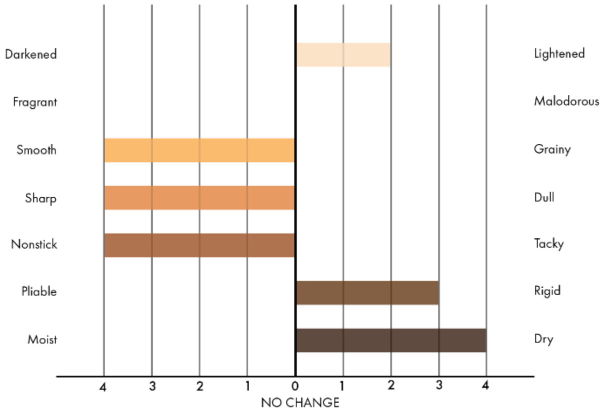
Chicken egg – Yolk

Chicken egg – Albumen, liquid

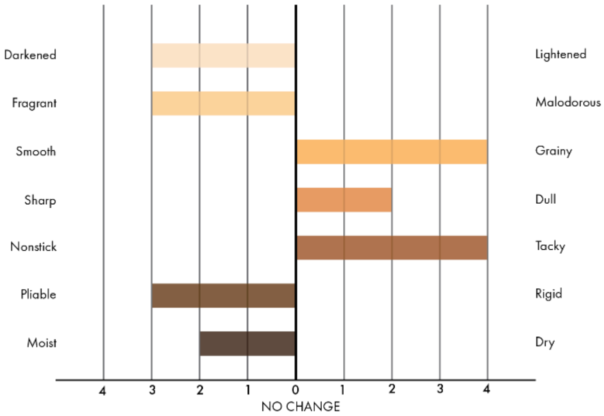
Chicken egg – Albumen, solid (= dehydrated)

Observed changes – most promising binders

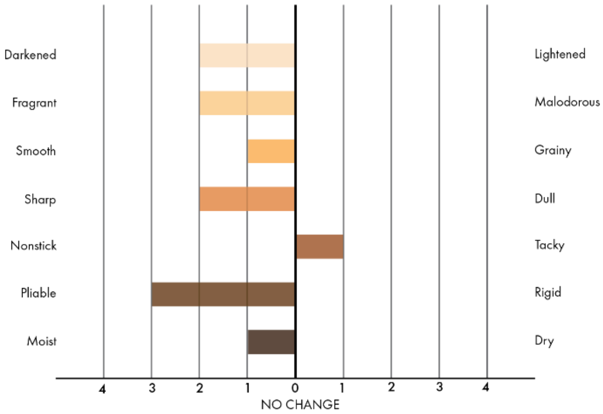
Cement



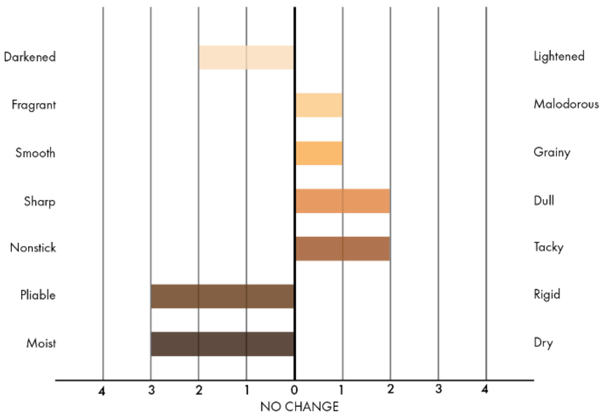
Sugar: 5%



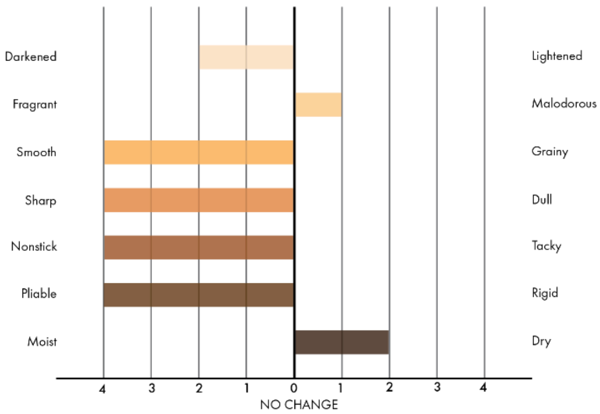
Sugar: 2%



Albumen: liquid



Albumen: solid



4.1.2. Drop test

Execution drop test

Requirements

For the drop test, there are no requirements.

Desired results

The desired result of the drop test is a sample comparison to predetermined visual outcomes, noting the visual changes representing the drop damage. The drop test is conducted to determine the appropriate moisture content of the mixture. The results of the drop test can be compared to the rule of thumb as described by three categories.

Highly fragmented – Minimally fragmented – Intact

These categories can be seen in *figure 17*, from left to right. If the sample is highly fragmented, the mixture is too moist. If the sample is minimally fragmented, the mixture is at optimum moisture levels. If the sample stays intact, the mixture can either be too dry or have too high of a clay content. If the intact sample feels dry, moisture is required. If the intact sample feels moist, the clay content should be lowered.

Fig. 17 - Highly fragmented – Minimally fragmented – Intact

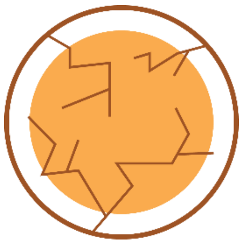


Fig. 18 - Desired binder result

Test process

The test process of the drop test remained unchanged compared to the version of the consulted literature. See *Appendix 10. Mixture composition testing* for a description of the testing process.

Results drop test

The drop test was first conducted on a sample of the regular rammed earth mixture, with no added binders. As the material was acquired at optimum moisture content, the reference sample was, as expected, minimally fragmented after conduction of the drop test. By adding the proposed binders, the material behaved unlike the expected outcome. Although the expected breakage pattern did not happen, as all binders resulted in intact dropped samples, comparisons could still be observed.

For each sample type, the series of considered binder percentages are used in a drop test. Both the visual changes to the drop pattern and the acoustic changes in the sound of the drop are compared. The most suitable binder percentage is acoustically similar to the sound of the drop test using the regular material mixture, with no binder. Visually, the most suitable binder percentage results in an intact sample, with cracks forming within the sample *(represented in brown in figure 18)*. This sample is slightly wider than before the drop test *(original size represented in orange in figure 18, the new sample size is represented in brown)*.

4.1.3. Shrink box test

Execution shrink box test

Requirements

- Shrink box formwork
  Length: 60cm.
  Width: 4cm.
  Height: 4cm.
- Rammer
  Note: rammer must fit in shrink box formwork.
- Boiled linseed oil
  Note: necessary for prepping the formwork.
- Paint tray
  Note: necessary for holding boiled linseed oil.
- Paint brush
  Note: necessary for applying boiled linseed oil.
- Palette knife
  Note: necessary for removing excess mixture.

Fig. 19 - Shrink box

Fig. 20 - Top: 5% sugar.
Middle: 2% sugar.
Bottom: no binder.

Desired results

The desired result of the shrink box test is a sample comparison, noting the linear length reduction of each sample. Maximum acceptable linear shrinkage is 3% of the length, or 1.8cm. It is advisable to stay under 2% linear shrinkage, or 1.2cm (Norton, 1997). This is an indication of the predicted shrinkage rate of the rammed earth construction. High percentages of shrinking equal fast drying of the material, resulting in high levels of cracking.

Test process

The test process of the shrink box test remained unchanged compared to the version of the consulted literature. See *Appendix 10. Mixture composition testing* for a description of the testing process.

Results shrink box test

All conducted shrink box tests had a linear shrinkage of less than 1 centimetre, passing both the norm for maximum and advisable linear shrinkage.

An interesting observation was made during the execution of the shrink box test with the use of granulated sugar as the binder. When compacted, the higher sugar content of samples results in the expression of excess moisture, although no additional moisture was added. Moreover, the appearance of the sample changes when more granulated sugar is added: the material darkens, in addition to having a grainy surface texture. These findings remain consistent even after complete drying of all samples. The active principle responsible for these observations is not found.

Fig. 21 - Left: no binder.
Middle: 2% sugar.
Right: 5% sugar.

4.1.4. Workability test

To execute the workability test, the instructions of the considered literature, described in the previous chapter, were followed. However, during the first round of sampling, no results comparable to the desired outcome were observed. The test intends to form a truncated cone sample of wet rammed earth mixture. After undergoing shocks applied by a drop table, the level of spreading of the cone is measured. In the executed test, there was little to no recorded spreading. For this reason, the workability test was not conducted further.

Fig. 22 – Truncated mould

4.1.5. Bar test

To execute the bar test, the instructions of the considered literature, described in the previous chapter, were followed. However, during the first round of sampling, no results comparable to the desired outcome were observed. The test intends to measure the level of sinking of the bar into the wet mixture sample. In the executed test, the depth of sinking of the bar was not or minimally recorded. Potentially, the large aggregate of the material prevents the bar from penetrating the loam part of the material. For this reason, the bar test was not conducted further.

Fig. 23 - Bar test set-up

4.1.6. Cigar test

To execute the cigar test, the instructions of the considered literature, described in the previous chapter, were followed. However, during the first round of sampling, no results comparable to the desired outcome were observed. Although acquired at supposed ´optimum´ moisture content for construction, the rammed earth mixture was too dry for accurate cohesion to perform the test. To counteract, more moisture was added to the mixture. Only at an additional moisture content of 10%, did the material pass the test. Although, the added moisture resulted in seemingly lowered functionality, making the material too fluid for compaction. For this reason, the cigar test was not conducted further.

4.2. Mechanical characteristics testing

4.2.1. Wetting and drying test

Execution – Wetting and drying test

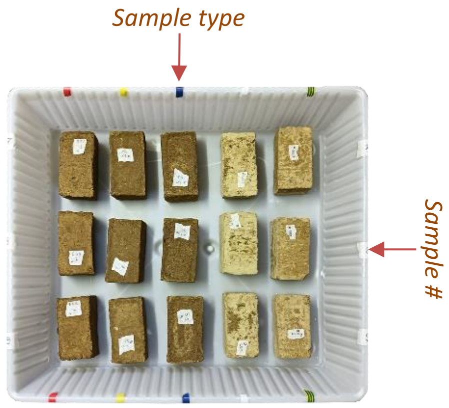


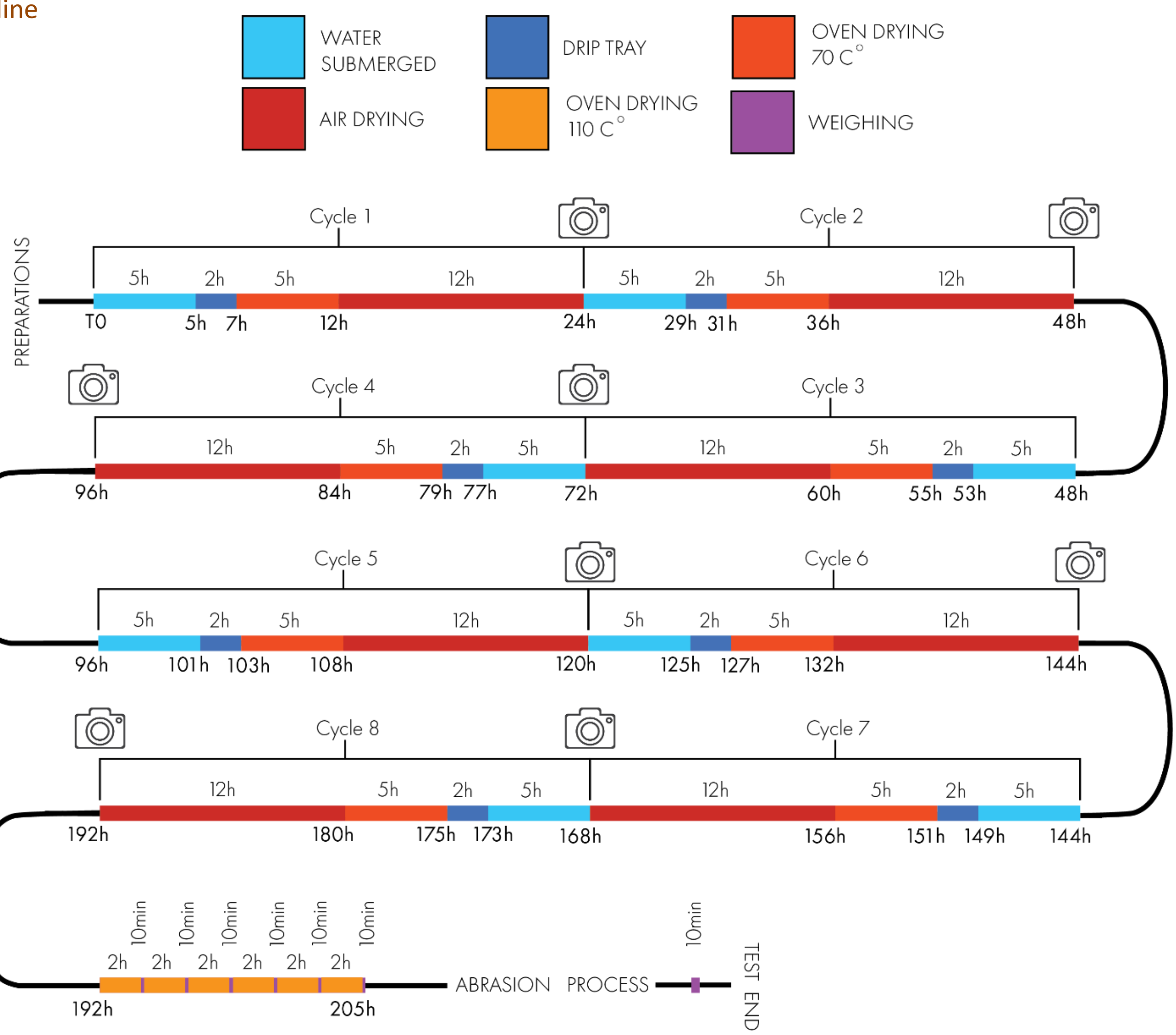
Fig. 24 - Container 1

Fig. 25 - Weighted steel brush

Requirements

- Container 1: water submerging
  Label horizontal axis: sample type.
  Label vertical axis: sample number.
- Container 2: drip tray
  Label horizontal axis: sample type.
  Label vertical axis: sample number.
- Scale
  Range: minimum 2.5kg.
  Precision: 1g.
- Weighted steel brush
  Weight brush: 224g.
  Added weight, splitting wedge: 2kg.
  Total weight: 2.224kg.
- Low temperature oven
  Temperature minimum: 50 degrees Celsius.
  Temperature maximum: 110 degrees Celsius.

Test timeline



Desired result

The desired result of the test is a sample comparison before and after test conduction, noting the final weight reduction and sensory-perceptual changes over time. This is an indication of the expected behaviour of the material, on account of the wetting and drying processes caused by alternating periods of heavy rainfall and intense sun-load (Norton, 1997).

Test process

Fig. 26 - Drying of samples

1. Prepare samples; labelling, weighing, recording results.
   6 sample types: 3x regular, 3x cement, 3x albumen liquid,
   3x albumen solid, 3x sugar 2%, 3x sugar 5%
2. Place samples in container 1.
   Note 1: place samples on predetermined location.
3. Fill container 1 with water *(T0).*
   Note 1: hit side of container with water, never directly on the samples.
   Note 2: water level 2cm above top of samples.
4. Move samples to container 2, the drip tray, for water drainage *(T0 + 5h).*
   Note 1: place samples on predetermined location.
   Note 2: do not hold samples using pinch grip,
   hold samples on long sides, using flat hands.
5. At end of wetting and drying test, place surviving samples in oven *(T0 + 7h).*
   Temperature: 110 degrees Celsius.
   Note 1: place samples on predetermined location.
6. Clean both containers.
   Note 1: discard debris.
7. Remove samples from oven *(T0 + 12h).*
   Note 1: 5 hours of oven time.
8. Place samples in clean container 1 *(T0 + 12h).*
   Note 1: place samples on predetermined location.
9. Completion cycle; note results *(T0 + 24h).*
   Note 1: results of sensory experiences in writing.
   Note 2: results of visual appearance in photographs.
10. Repeat step 1-7 seven times.
11. Start cycle 8 in accordance with step 1-3.
12. Place samples cycle 8 in oven, 110 degrees Celsius.
    Note 1: place samples on predetermined location.
13. Weigh samples cycle 8 every 2 hours, until consistent weight is reached.
    Note 1: for this test, 12 hours of oven time was conducted.
14. Removal of damaged areas samples; abrasion process.
    a. Place weighted brush on wedged in sample, bottom side 1.
    b. Move brush from bottom to top and back down.
       Note 1: hold brush with one hand on each side.
       Note 2: attempt to move the brush without added force.
    c. Repeat up-down movement 10 times.
       Note 1: 10 movement times = one cycle of abrasion.
    d. Repeat cycle of abrasion 3 times for all 6 sides.
       Note 1: abrasion cycle on 'left edge – centre – right edge' of each side.
       Note 2: 18 cycles of abrasion per sample.
    e. Repeat total cycles of abrasion on each surviving sample.
15. Weighing samples; final results.

Fig. 27 - Abrasion set-up

Results – Wetting and drying test

The results of the wetting and drying test can best be described using imagery, the overview of each test interval can be seen in the illustrations below. The findings of these visual results are discussed per sample type in the radar charts following the overview. The sample types of which samples lasted the whole duration of the tests without damage are 'Cement', 'Albumen: liquid', and 'Albumen: solid'.

Note: Because the regular samples, with no binder, dissolved after the first round of water submerging, these samples are not included in the images. For this reason, the order of the samples in the illustrations also does not follow the regular order in this document. The order and related colours are as followed:

See Appendix 13 – Wetting and drying test – Images, for detailed images.

Red – Yellow – Blue – White – Striped/**Black**
Albumen: Liquid – Sugar: 2% – Sugar: 5% – Cement – Albumen: Solid

Cycle 1 - 5 hours water submerging

Red – Yellow – Blue – White – Striped/**Black**
Albumen: Liquid – Sugar: 2% – Sugar: 5% – Cement – Albumen: Solid

Cycle 2 - 10 hours water submerging

Cycle 3 - 15 hours water submerging

Red	Yellow	Blue	White	Striped/**Black**
Albumen: Liquid	Sugar: 2%	Sugar: 5%	Cement	Albumen: Solid

Cycle 4 - 20 hours water submerging

Cycle 5 - 25 hours water submerging

Red – Yellow – Blue – White – Striped/**Black**

Albumen: Liquid – Sugar: 2% – Sugar: 5% – Cement – Albumen: Solid

Cycle 6 - 30 hours water submerging

Cycle 7 - 35 hours water submerging

Red – Yellow – Blue – White – Striped/**Black**
Albumen: Liquid – Sugar: 2% – Sugar: 5% – Cement – Albumen: Solid

Cycle 8 - 40 hours water submerging

Comparative results

A few of the samples of the types ‘Albumen: liquid’ and ‘Albumen: solid’ broke in half during the testing process. This most likely could have been avoided by applying proper handling during movement of samples. A pinch grip was applied during lifting, causing the weak points due to water damage to separate the blocks. When moving the samples with a flat hand on each long side of the samples, no such damage occurs.

Broken sample ‘Albumen: solid’

(Round 6)

(Round 7)

(Round 8)

The samples of ‘Albumen: liquid’ disintegrate as soon as broken; the blocks separate into the various layers in the sample. The samples of ‘Albumen: solid’ do not disintegrate, even when broken. They do, however, also decrease in total material.

Albumen: liquid – Round 3
(All samples)

Albumen: liquid – Round 8
(Surviving sample)

For both albumen sample types their none broken counterparts do withstand the testing. However, the surviving sample of 'Albumen: liquid' does show hairline cracks indicating expansion due to water absorption. This is a clear damage pattern and indication of weakness to swelling by water absorption.

Round 2 – detail overview

Sugar 5%

Sugar 2%

Round 3 – detail overview

Sugar 5%

Sugar 2%

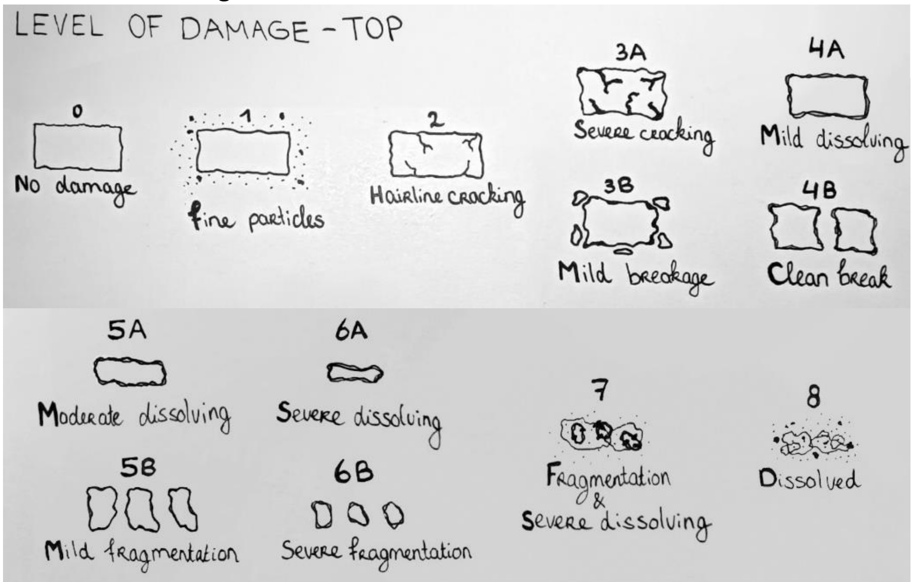
A detailed view of the sample types 'Sugar 5%' And 'Sugar 2%' after the second and third round are provided above. This is done to show the quickly occurring damage between the two rounds. As can be seen, the samples containing 5% sugar quickly shrink in size, but do so proportionally in all directions.

The samples containing 2% sugar lose their fine particles (sand, loam, smaller pebbles) significantly sooner than their larger parts (larger pebbles). These larger pebbles become the outside 'shell' of the sample, holding the interior finer parts in place. This is in accordance with predicted weathering patterns, where the larger aggregates protect the interior of rammed earth walls (Rauch, 2020).

Interpretation wetting and drying test

To interpret the images given above, radar charts are made with the following categories:

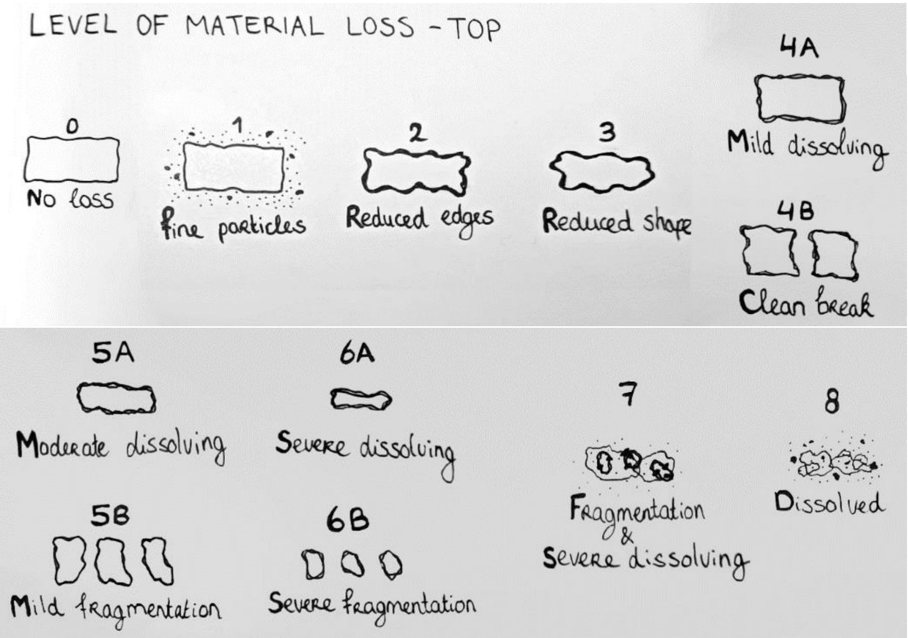
- Level of damage



2

2

- Level of material loss



1

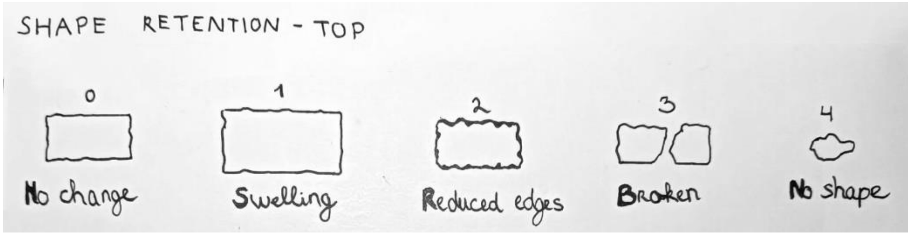
3

- Texture change

4

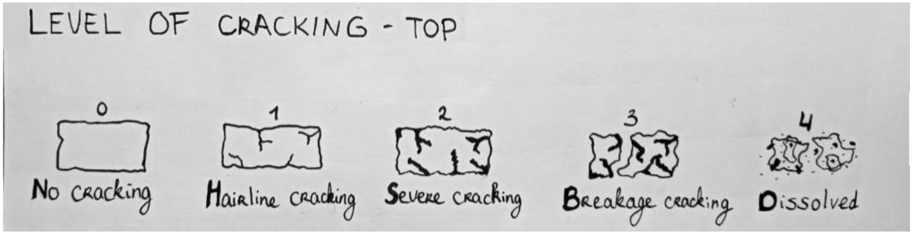
5

– Shape retention



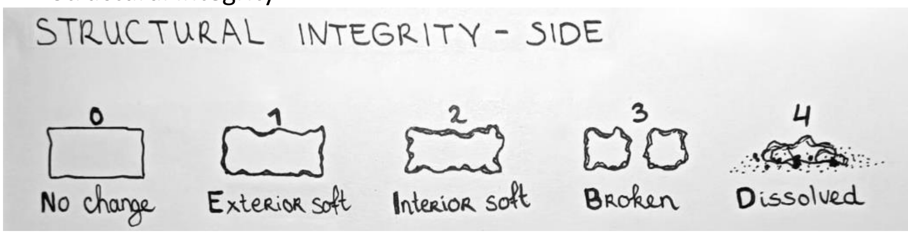
3
6

– Level of cracking



5
7

– Structural integrity

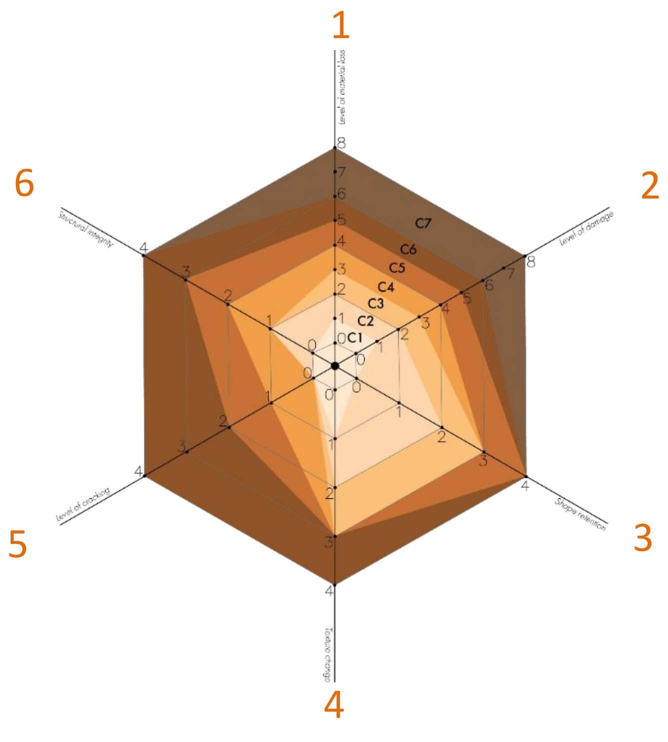


6
8

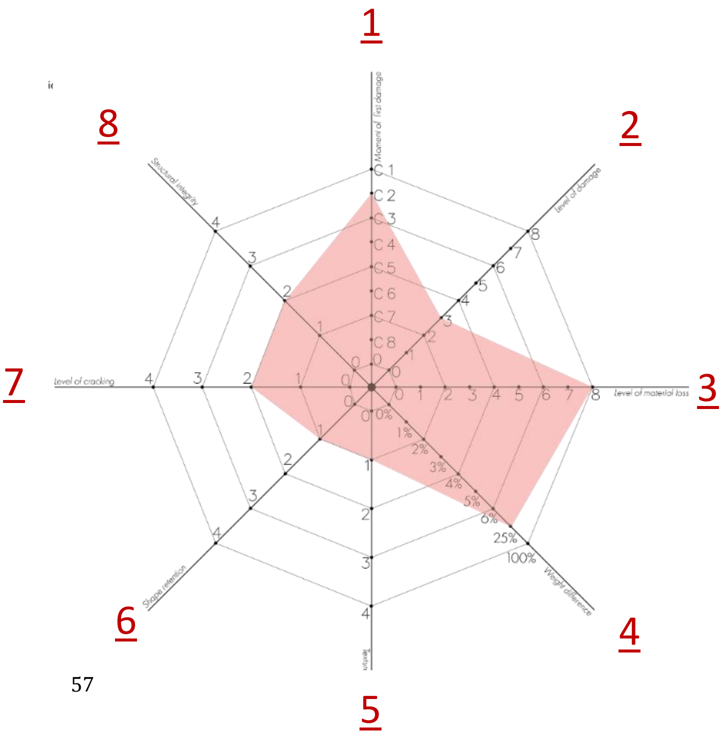
– Moment of first damage
C1 to C8, representing each wetting & drying cycle of the test. Measured per 24 hours. 1

– Weight difference
Measured before start of testing and after oven drying at end of testing. Expressed in percentage of starting weight, given that every sample has a different starting weight. 4

Example process chart



Example result chart



Overview results – Wetting & drying test

As can be seen in *table 7*, marked in green, only the samples containing albumen and the samples containing cement survived the wetting and drying test. This means they potentially have a level of resistance against water damage required to use the material for structural use.

Sample type	Individual scores	Total scores	Moment of total dissolving	Rank
Regular 1	48	144	C1	6
Regular 2	48		C1	
Regular 3	48		C1	
Albumen: liquid 1	47	119	C6	3
Albumen: liquid 2	25		*n/a*	
Albumen: liquid 3	47		C6	
Sugar: 2% 1	48	144	C7	4
Sugar: 2% 2	48		C7	
Sugar: 2% 3	48		C7	
Sugar: 5% 1	48	144	C5	5
Sugar: 5% 2	48		C5	
Sugar: 5% 3	48		C5	
Cement 1	7	24.5	*n/a*	1
Cement 2	8.5		*n/a*	
Cement 3	9		*n/a*	
Albumen: solid 1	9	49.5	*n/a*	2
Albumen: solid 2	11.5		*n/a*	
Albumen: solid 3	29		*n/a*	

Table 7 - Overview results – wetting & drying test

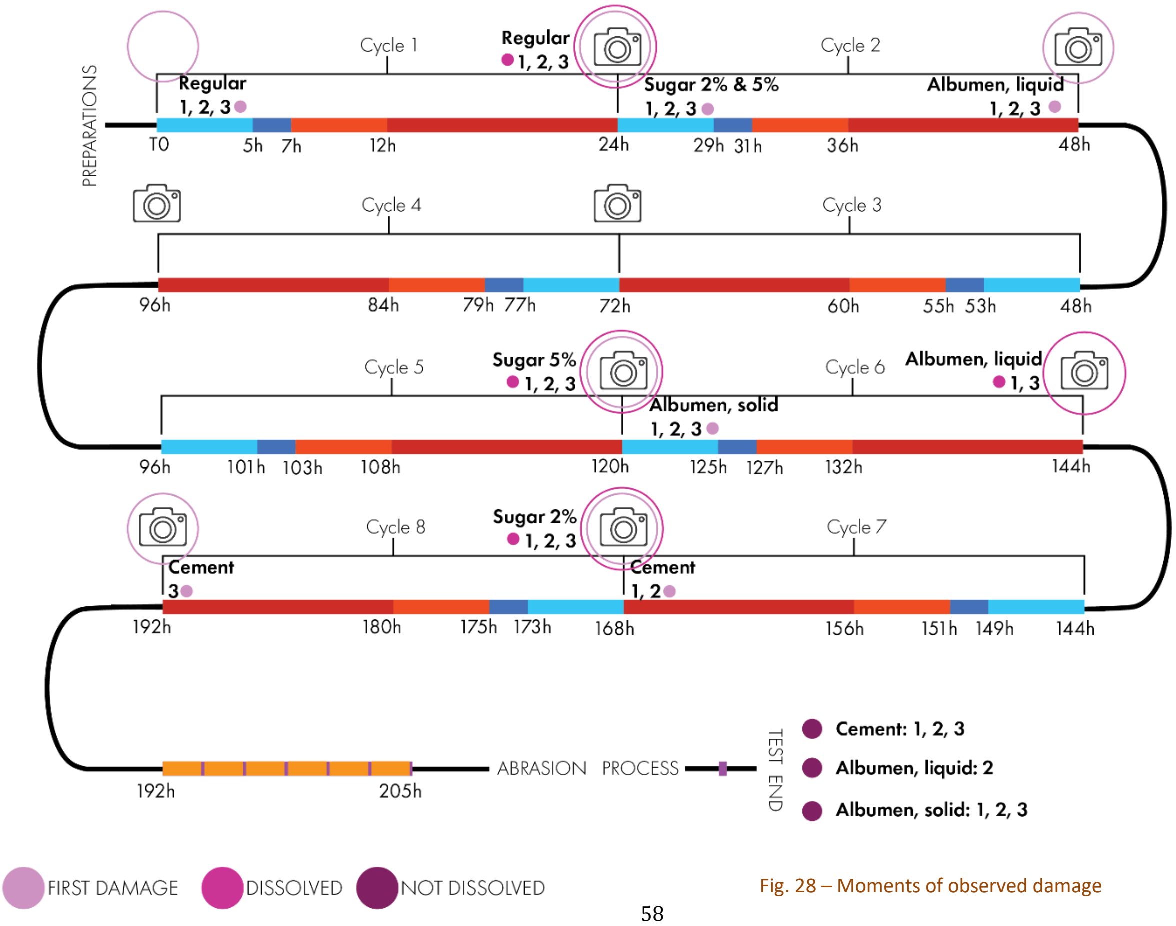


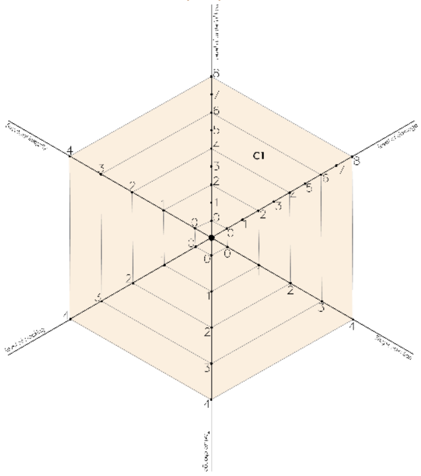
Fig. 28 – Moments of observed damage

Overview damage progression – Wetting and drying test

See Appendix 14 – Wetting and drying test – Results, for detailed images

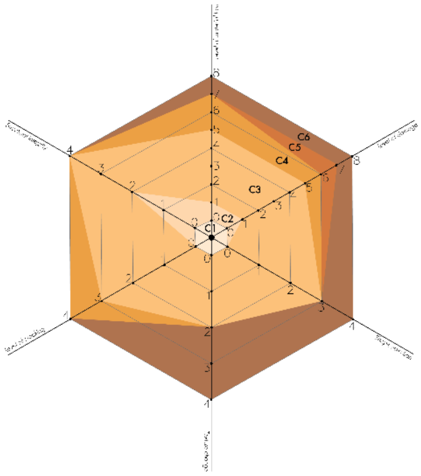
Regular

1, 2, 3

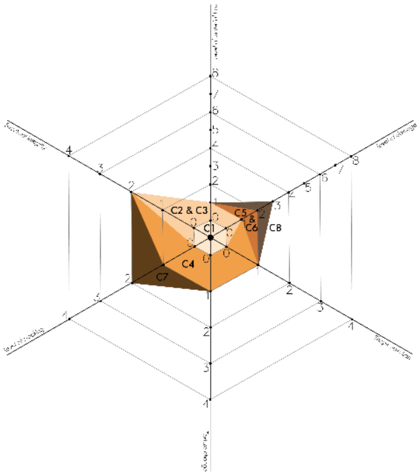


Albumen: liquid

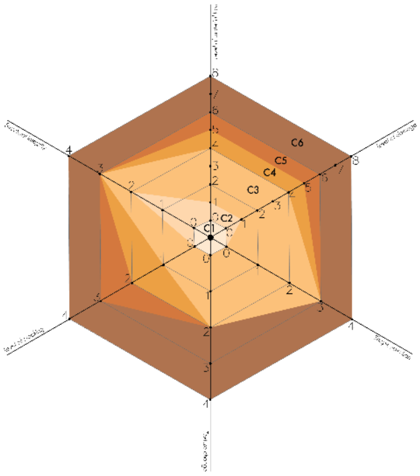
1



2

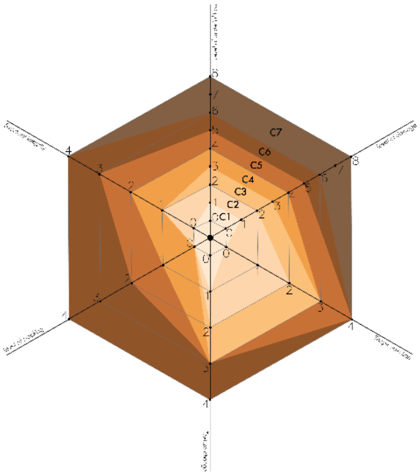


3

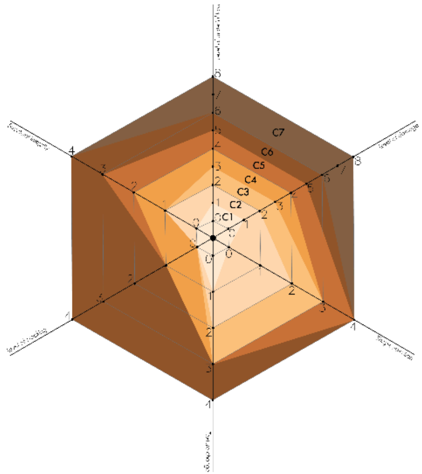


Sugar: 2%

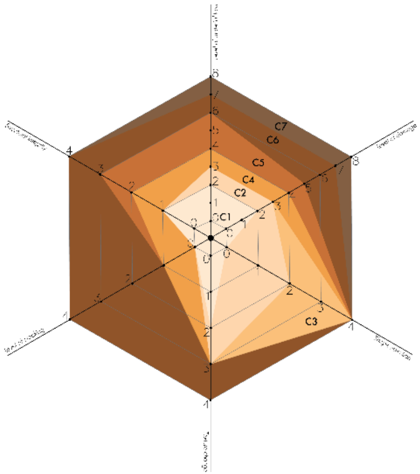
1



2

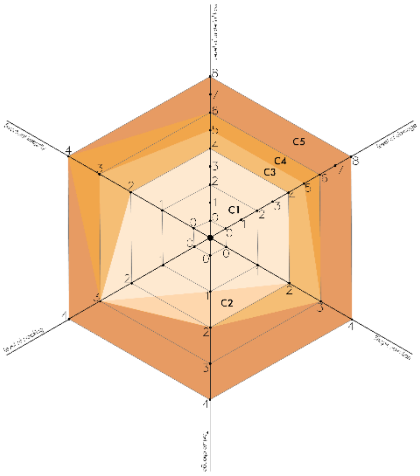


3

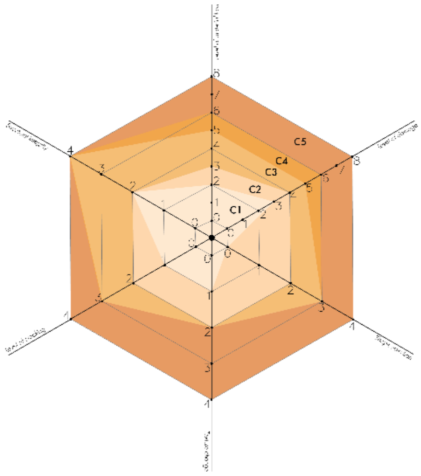


Sugar: 5%

1



2



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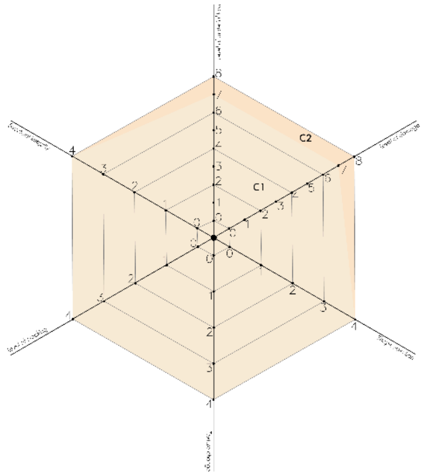
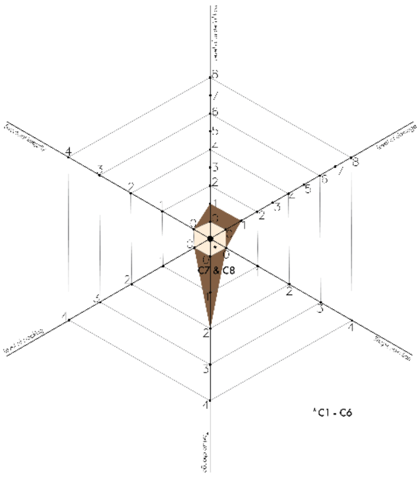
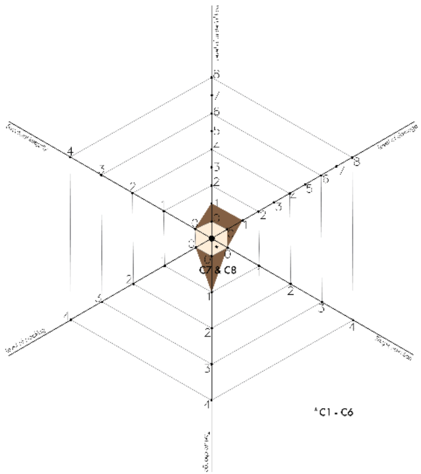


Cement

1



2



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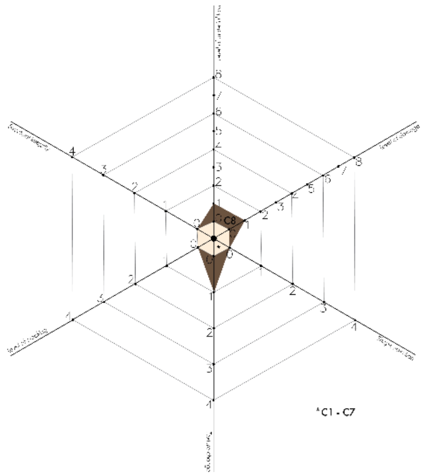
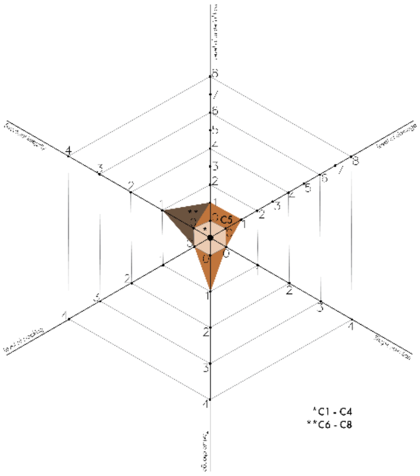


Albumen: solid

1



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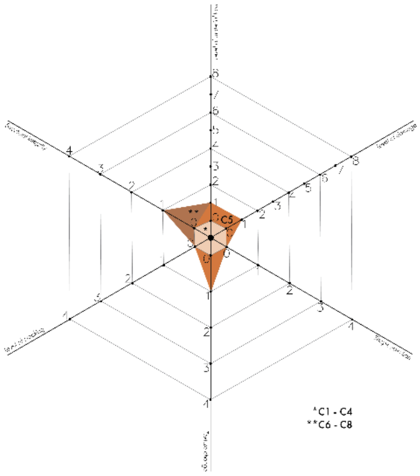

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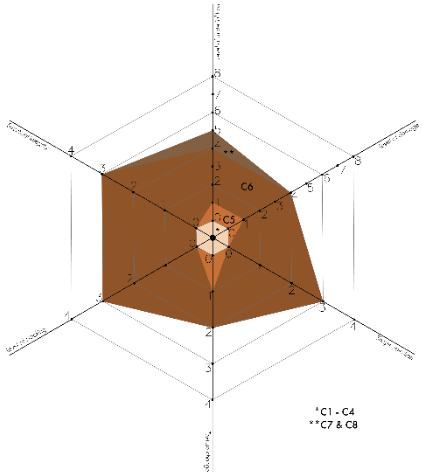
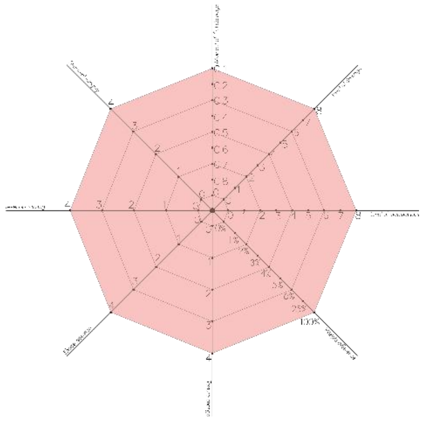


Overview final damage – Wetting and drying test

See Appendix 14 – Wetting and drying test – Results, for detailed images

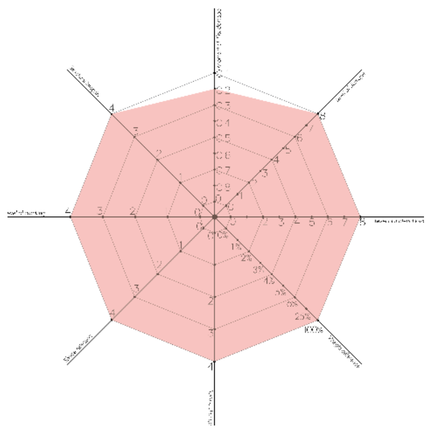
Regular

1, 2, 3

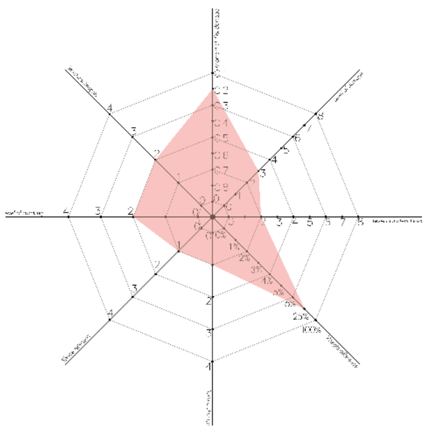


Albumen: liquid

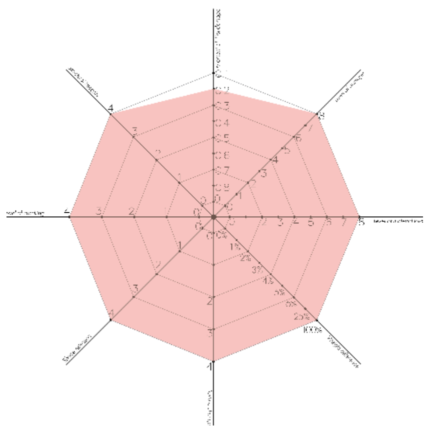
1



2

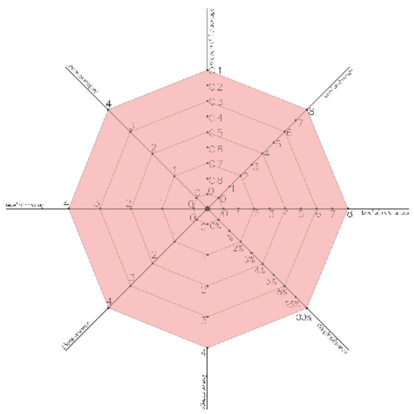


3



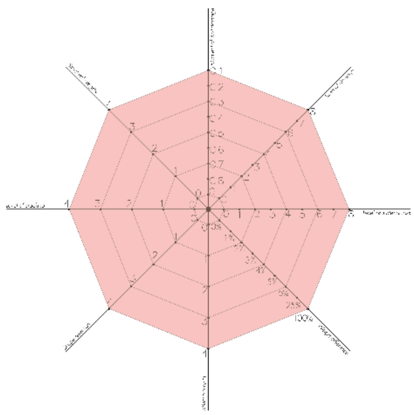
Sugar: 2%

1, 2, 3



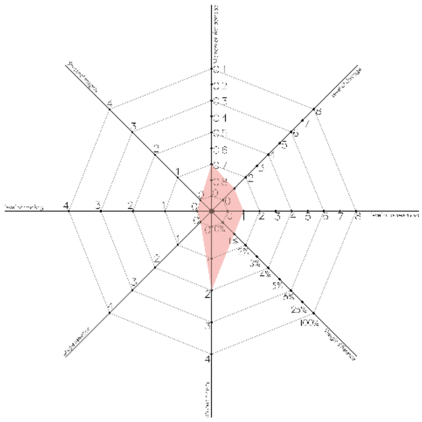
Sugar: 5%

1, 2, 3

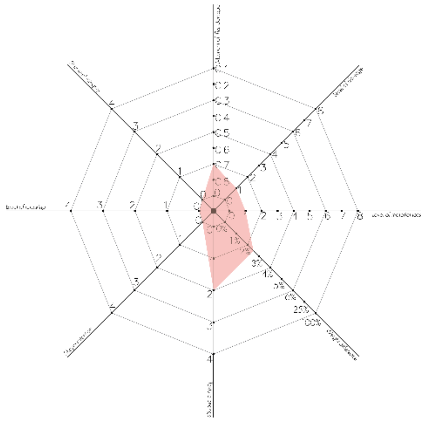


Cement

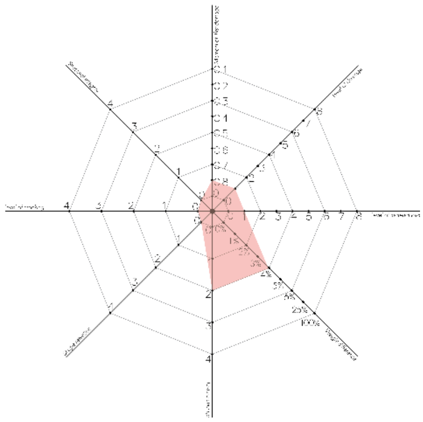
1



2

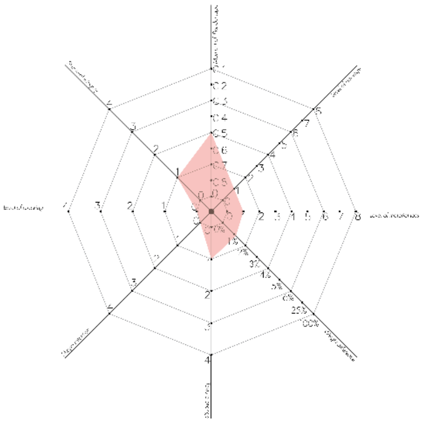


3

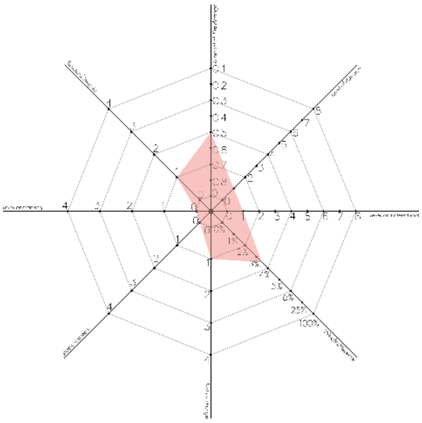


Albumen: solid

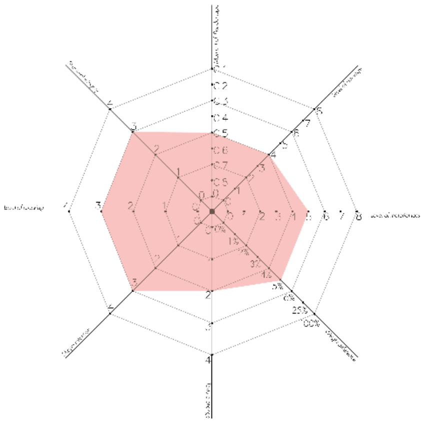
1



2



3



4.2.2. Abrasion test

Execution – Abrasion test

Requirements

- Sample support
  Set-up to prevent samples from movement
- Scale
  Range: minimum 2.5kg.
  Precision: 1g.
- Weighted steel brush
  Weight brush: 224g.
  Added weight, splitting wedge: 2 x 2kg.
  Total weight: 4.224kg.

Fig. 29 - Weighted steel brush

Desired result

The desired result of the test is a sample comparison before and after test conduction, noting the weight reduction and visual changes. This is an indication of the vulnerability of the resulting material against everyday wear-and-tear as a result of contact damage (Minke, 2000).

Test process

1. Prepare samples; labelling, weighing, recording results.
   6 sample types: 2x regular, 2x cement, 2x albumen liquid,
   2x albumen solid, 2x sugar 2%, 2x sugar 5%
2. Place samples on sample support.
   Note 1: wedge samples in to prevent, or limit, sample movement.
3. Place weighted brush on wedged in sample,
   Note 1: place on long, layered side.
   Prevent abrasion on top or bottom.
4. Move brush from left to right and back to left:
   1 cycle of abrasion.
   Note 1: hold brush with one hand on each side.
   Note 2: attempt to move the brush without added force.
5. Repeat for 50 cycles of abrasion.
6. Repeat total cycles of abrasion on each sample.
7. Weighing samples; final results.

Fig. 30 - Abrasion test set-up

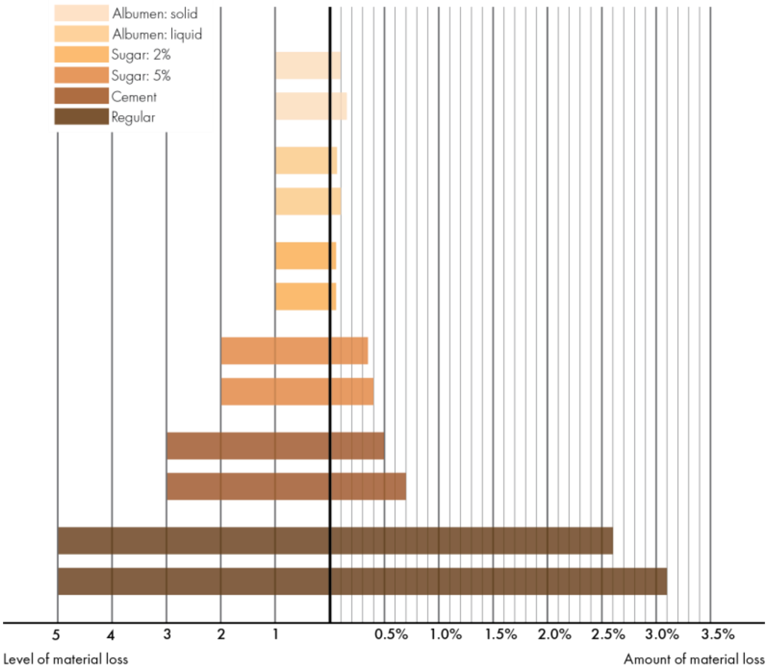
Fig. 31 - Cycle of abrasion.

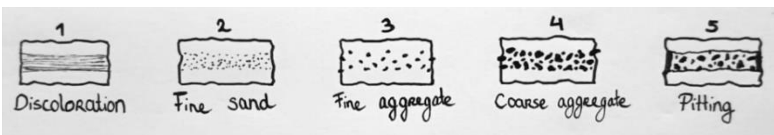
Results – Abrasion test

The results of the abrasion test can best be described using imagery. The sample types that showed minimal damage are ‘Albumen: solid’, ‘Albumen: liquid’, and ‘Sugar: 2%’.

As can be seen in *table 8*, the samples marked in green have less than 1% material loss during the abrasion test and only show discoloration damage. This means they potentially have a level of resistance against abrasion required to use the material for use in construction, to prevent excessive daily wear and tear.

Visualisation results abrasion





**Note: one of the samples containing 5% sugar is broken. The breakage is not related to the testing.*

Sample type	Material loss	Rank
Albumen: solid	- 0,10% - 0,16%	3
Albumen: liquid	- 0,05% - 0,11%	2
Sugar: 2%	- 0,05% - 0,05%	1
Sugar: 5%	- 0,33% - 0,42%	4
Cement	- 0,48% - 0,70%	5
Regular	- 2,58% - 3,10%	6

Table 8 - Overview results – abrasion test

4.2.3. Penetration test

Execution – Penetration test

Requirements

- Sharp object, ex. knife
  Note: thick blade is necessary to prevent bending or breakage
- Measuring tool, ex. scale bar
  Note: must be able to stand upright on sample
- Scale
  Range: minimum 2kg.
  Precision: 10g.

Fig. 32 - Penetration test tool

Desired result

The desired result of the test is a visual representation of the amount and type of damage due to penetration. This is an indication of the vulnerability of the resulting material against incidental wear-and-tear as a result of impact damage (Minke, 2000).

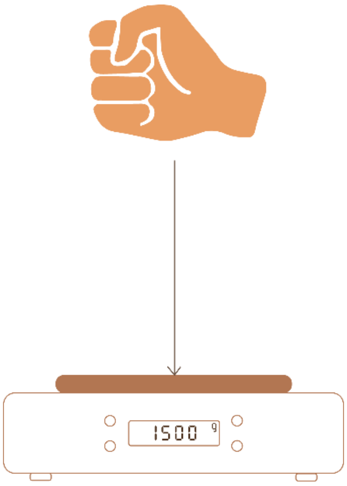


Fig. 33 - Penetration force

Test process

1. Prepare samples; labelling.
   6 sample types: 3x regular, 3x cement, 3x albumen liquid,
   3x albumen solid, 3x sugar 2%, 3x sugar 5%
2. Prepare penetration force.
   a. *Strike scale with fist of dominant hand, observe resulting weight*
   b. *Repeat until consistent average striking force of 1.5kg is obtained.*
3. Prepare measuring tool.
   Note 1: mark at 8cm.
   Note 2: ensure mark is easily visually notable.
4. Place measuring tool on the top of a sample.
5. Hold the sharp object at the marked distance above the sample.
6. Penetrate sample with prepared striking force.
   Note 1: force of 1.5kg.
   Note 2: minimum of 5 times.
7. Note results, visually and in writing.
8. Penetrate sample with maximum possible striking force.
   Note 1: minimum of 5 times.
9. Note results, visually and in writing.
   Note 1: concludes one cycle of penetration.
10. Repeat cycle of penetration for the bottom of the sample.
11. Repeat steps 1 till 10 for each sample.

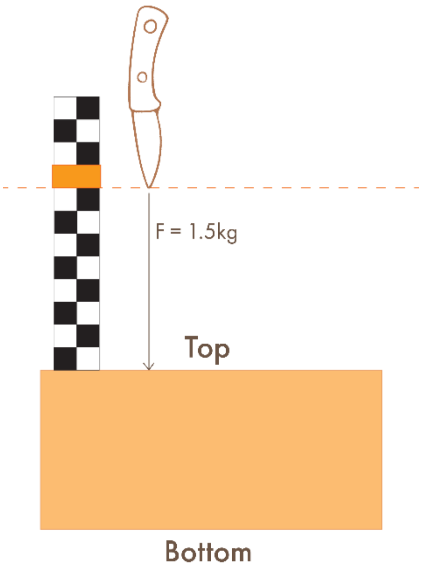


Fig. 34 - Penetration test set-up

Results – Penetration test

The results of the penetration test can best be described using imagery. None of the samples showed concerning levels of damage, however, each sample displayed different behaviour to the testing process.

Regular

Top

Bottom

Regular	Penetration type	Damage type
Top	Crumbling	Flat wide pitting
Bottom	Flaking	Deep narrow pitting

Cement

Top

Bottom

Cement	Penetration type	Damage type
Top	Chipping	Shallow pitting
Bottom	Chipping	Shallow pitting

Sugar: 5%

Top

Bottom

Sugar: 5%	Penetration type	Damage type
Top	Clean cuts	Knife marks
Bottom	Clean cuts	Knife marks

Sugar: 2%

Top

Bottom

Sugar: 2%	Penetration type	Damage type
Top	Clean cuts	Knife marks
Bottom	Clean cuts	Knife marks

Albumen: Liquid

Top

Bottom

Albumen: liquid	Penetration type	Damage type
Top	Flaking	Shallow pitting
Bottom	Clean cuts	Knife marks

Albumen: Solid

Top

Bottom

Albumen: solid	Penetration type	Damage type
Top	Clean cuts	Knife marks
Bottom	Clean cuts	Knife marks

Although interesting to observe the difference in penetration type and damage type, this is no indication for the usability level of use in construction. To conclude the ranking score, the amount of visible damage is combined with the depth of penetration.

Sample type	Penetration depth Top	Penetration depth Bottom	Rank
Regular	8mm - 4	6mm - 3	5
Cement	2mm - 1	2mm - 1	4
Sugar: 5%	8mm - 4	10mm - 5	6
Sugar: 2%	6mm - 3	6mm - 3	2
Albumen: liquid	4mm - 2	4mm - 2	3
Albumen: solid	2mm - 1	2mm - 1	1

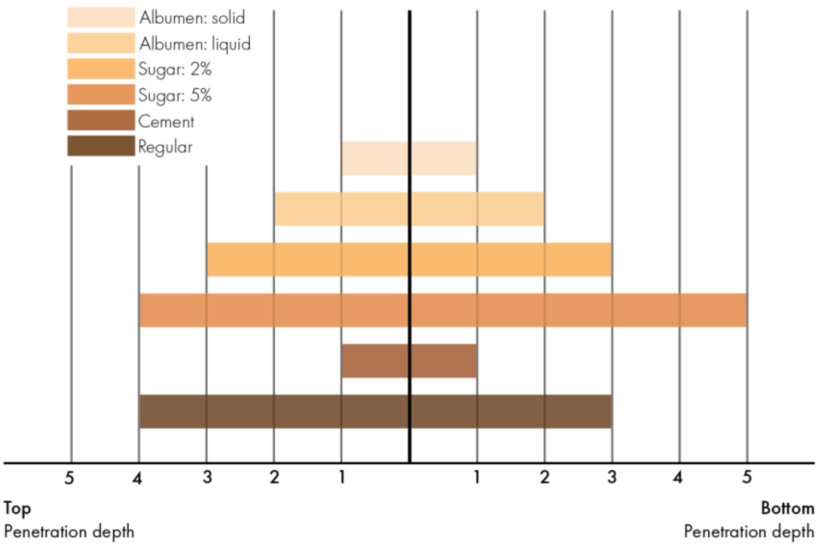
Table 9 - Overview results - penetration test

Fig. 35 - Penetration depth scale

As can be seen *table 9*, marked in green, the sample types 'cement', 'albumen: liquid', and 'albumen: solid' have a minimal penetration depth in relation to the used knife.

The measurements are rounded to fit within depth intervals of 2mm. The overview provides an indication of the ease of damage done to the material. Minimal levels of penetration indicate the samples potentially have a level of resistance against penetration required to use the material in construction, to prevent excessive daily wear and tear.

Results penetration test



4.2.4. Impact test

Execution – Impact test

Requirements

- Recording device
- Recording space
  Note: space should be devoid of background noise.

Desired result

The desired sound of a well-constructed rammed earth sample resembles that of the ringing sound of fired bricks (Minke, 2000). Therefore, the desired result of the test is a set of sound recordings to be compared to the sounds of both modern and historic fired bricks. This is an indication of the level of compaction, and therefor strength, of the resulting material (Houben & Guillaud, 1994).

Test process

1. Prepare samples; labelling.
   8 sample types: 2x regular, 2x cement, 2x albumen liquid,
   2x albumen solid, 2x sugar 2%, 2x sugar 5%,
   2x modern fired bricks, 2x historic fired bricks
2. Place recording device.
   Height: elbow height.
   Distance to sample: 10cm.
3. Start recording.
4. Place arms perpendicular to each other, one sample in each hand.
   Note 1: use two identical samples.
5. Strike samples against each other.
   Note 1: strike with long sides. Avoid top or bottom of samples.
   Note 2: strike with intensity of slow clapping.
6. Repeat strike
   Note 1: minimum of 3 times.
7. Stop and save recording.
8. Repeat for each sample type.

Results – Impact test
None of the samples showed a strong likeness in sound to the compared fired brick samples. However, some samples showed a duller sound than others. No clear findings can be determined from the test results.

4.2.5. Compressive and flexural strength test

Execution – Compressive and flexural strength test

Requirements
- Compressive strength testing machinery
- Flexural strength testing machinery

Desired result
The desired result of the compressive and flexural strength test is a data set illustrating the force required to reach sample breaking point. Combined with available data on other structural materials, this indicates comparative load-bearing capabilities. Additionally, the data provides the knowledge to dimension a sufficiently strong structure (Houben & Guillaud, 1994).

Fig. 36 - Test set-up

Test process
- Compressive strength test: equal to that of the *'Method for the Determination of the Compressive Strength of Hardened Concrete' (NEN-EN 12390-3:2019 en)* (NEN, 2019).
- Flexural strength test: equal to that of the *`Standard Test Method for Flexural Strength of Concrete´ (ASTM C293/C293M - 15 en)* (NEN, 2015).

Results – Compressive and flexural strength test
Although the tests were conducted using standardised machinery and test processes, the results were deemed not reliable. The machinery kept executing the test, even when breaking points were previously achieved. Two visual observations could be made during testing. The first observation is that binder use prolongs test duration. The second observation is that cement makes the material crumble under load, while the bio-based binders hold the material together, resulting in clean breaks.

4.3. Weathering testing

4.3.1. Drip test

Execution – Drip test

Requirements

- Test location
  Indoors: preventing test interruption due to wind.
  Attachment rig: 30cm space between sample types.
  Attachment rig: nozzle 2m above sample.
  Water source available.
- Containers with adjustable drip nozzle
  In this test: copper tubing attached to bottle lids.
- Pliers
  Use: adjusting drip rate.
- Pouring cup
  Volume: minimum total ml of one container.
- Drip tray, 6x
  Label horizontal axis: sample type.
- Angled support, 6x
  Angle of sample: 45 degrees.
- Scale
  Range: minimum 2.5kg.
  Precision: 1g.
- Low temperature oven
  Temperature: 110 degrees Celsius.
- Toothpicks
- Marker
- Ruler

Fig. 37 - Drip nozzle

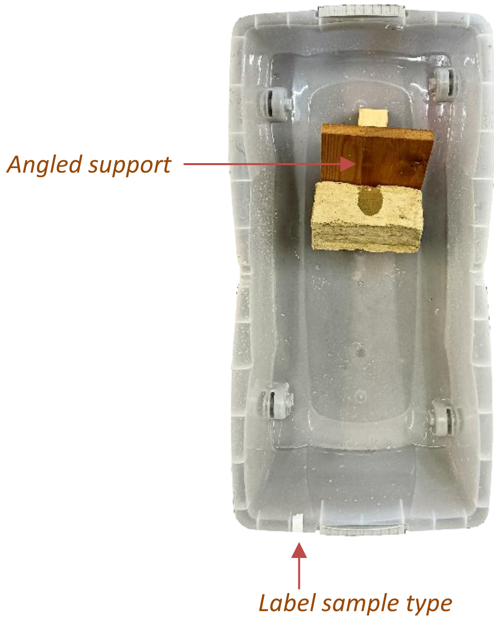


Fig. 38 - Drip tray

Desired result

The desired result of the drip test is a sample comparison before and after test conduction, noting the weight reduction, depth of pitting, and visual changes. This is an indication of the predicted damage done by persistent water erosion (Houben & Guillaud, 1994).

Test process

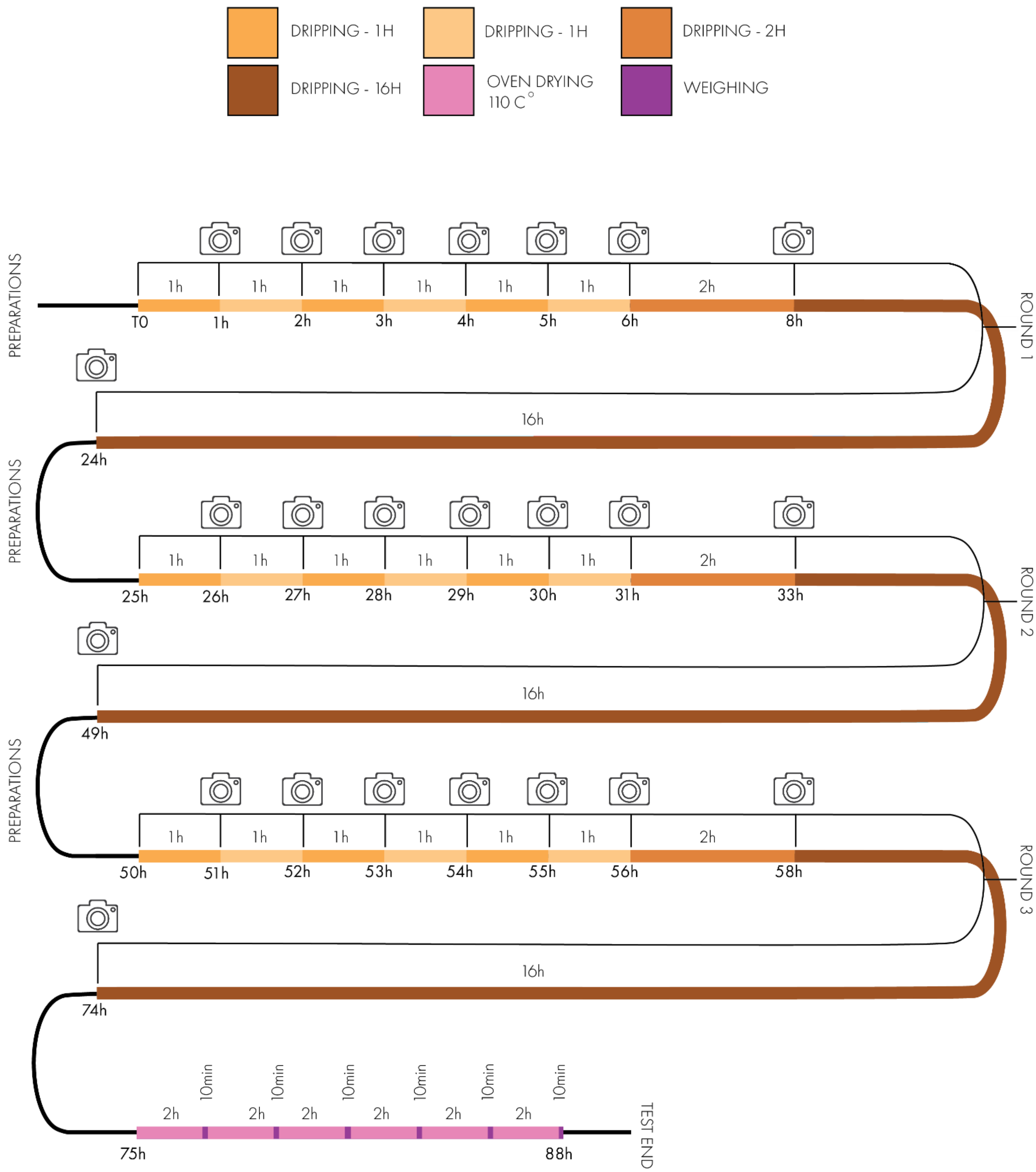
1. Prepare samples;
   labelling, weighing, recording results.
   6 sample types: 3x regular, 3x cement,
   3x albumen liquid, 3x albumen solid,
   3x sugar 2%, 3x sugar 5%
2. Mark samples.
   Mark on centre of a layered side.
3. Measure water volume of nozzle containers.
   Note 1: For this test, a volume
   of 450ml is observed.

Fig. 39 - Drip test set-up

4. Hang nozzle containers on attachment rig.
   Note 1: in this test, the attachmen rig is a structural beam.
5. Place all drip-trays centred under nozzles.
6. Place all angled supports centred in drip-trays.
7. Fill nozzle containers with water.
   Note 1: Fill each container with predetermined water volume.
   Note 2: For this test, a volume of 450ml is observed.
8. Adjust drip rates.
   Note 1: For this test, a drip rate of 30 drips/minute is chosen. This equals to 0.27 l/hour.
   a. Start a timer of 20 seconds.
   b. Count fallen drops per nozzle until timer runs out.
   c. Adjust with pliers, closing or opening the nozzle.
   d. Continue until each nozzle has a drip rate of 10 drops/20 seconds.
9. Empty all nozzle containers.
10. Fill nozzle containers with water.
    Note 1: Fill each container with predetermined water volume.
    Note 2: For this test, a volume of 450ml is observed.
11. Place samples on angled supports *(T0)*.
    Note 1: place samples in predetermined drip-tray.
    Note 2: one sample of each type is used per round.
12. Check on test at set intervals.
    Intervals: (T0 + 1h) (T0 + 2h) (T0 + 3h) (T0 + 4h) (T0 + 5h) (T0 + 6h) (T0 + 8h) (T0 + 24h)
    a. Move drip-trays straight backwards, until samples are out of the drip-stream.
    b. Empty all nozzle containers.
    c. Record damage, visually and in writing.
    d. Fill nozzle containers. *See step 9.*
    e. Adjust drip rates as needed. *See step 7.*
    f. Empty all nozzle containers.
    g. Move drip-trays straight forwards, until samples are in the drip-stream.
    h. Fill nozzle containers. *See step 9.*
    i. Ensure that the drip-streams hit each sample on the marked location.
13. At end of drip test, place surviving samples in the oven.
    Temperature: 110 degrees Celsius.
    Note 1: place samples on predetermined location.
14. Weigh samples every 2 hours, until consistent weight is reached.
    Note 1: for this test, 12 hours of oven time was conducted.
15. Weighing samples; final results.
16. Measuring depth of pitting; final results.
    a. Place toothpick in deepest area of pitting.
    b. Mark toothpick at sample surface.
    c. Remove toothpick.
    d. Measure distance from toothpick tip to marking.
17. Finish round 1.
    Note 1: finishing step 1 to 15 concludes round 1.
    Note 2: repeat for round 2.
    Note 3: repeat for round 3.

Fig. 40 - Drying of samples

Test timeline



Test set-up experimentation

The described drip-method for this test exists of a large container of water with a saturated absorbent thread. Below are the considered tested threads. *(See figure 41. Left to right: cotton shoelace, synthetic shoelace, cotton wool, cotton string, cotton fabric strip 1cm, cotton fabric strip 3cm, cotton fabric strip 5cm).* The steadiest drip was obtained using cotton fabric strips with a 5cm width. However, the drip-rate was not consistent for each sample type. Moreover, the test resulted in an insufficient drip volume: only 15ml/6 hours, *see figure 42*.

Fig. 41 - Drip test experimentation - material choice

Fig. 42 - Drip test experimentation - drip rate determination

Results – Drip test

The results of the drip test can best be described using imagery, the complete overview of each test interval can be seen in the illustrations below. The findings of these visual results are discussed per sample type in the table following each round overview. The sample types lasting the whole duration of the tests without damage are 'Cement', 'Albumen: liquid' and 'Albumen: solid'. The checking is done at 8 intervals:

1 hour – 2 hours – 3 hours – 4 hours – 5 hours – 6 hours – 8 hours – 24 hours

1 Hour *2 Hours* *3 Hours* *4 Hours*

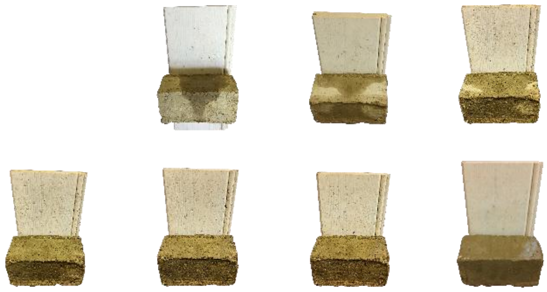
5 Hours *6 Hours* *8 Hours* *24 Hours*

See Appendix 15. Drip test – Images, for detailed images.

Drip test results – First round

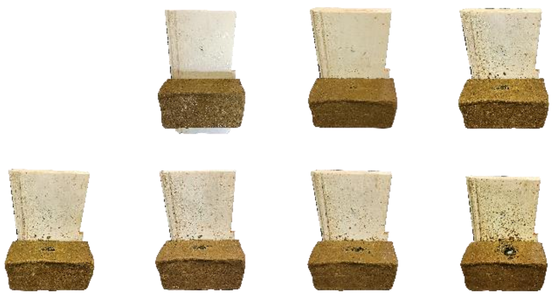
Round 1 - Regular

Round 1 - Cement

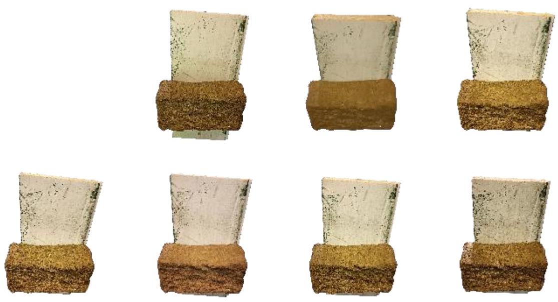


Round 1 - Sugar: 5%

Round 1 - Sugar: 2%



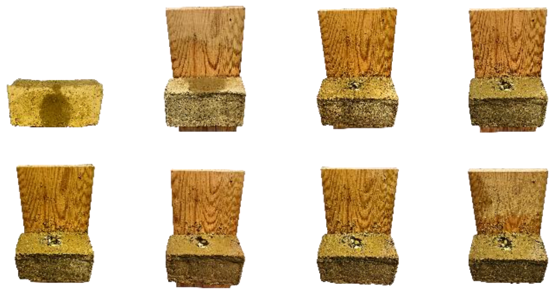
Round 1 - Albumen: Liquid



Round 1 - Albumen: Solid

Drip test results – Second round

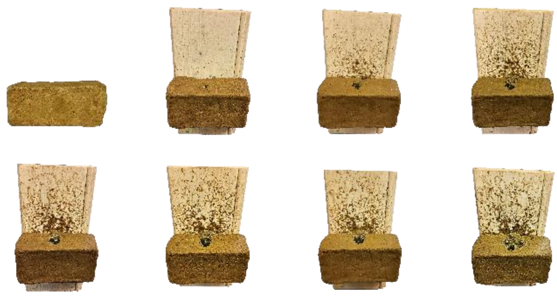
Round 2 - Regular



Round 2 - Cement

Round 2 - Sugar: 5%

Round 2 - Sugar: 2%



Round 2 - Albumen: Liquid

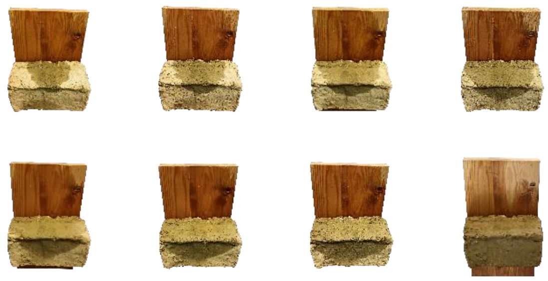
Round 2 - Albumen: Solid

Drip test results – Third round

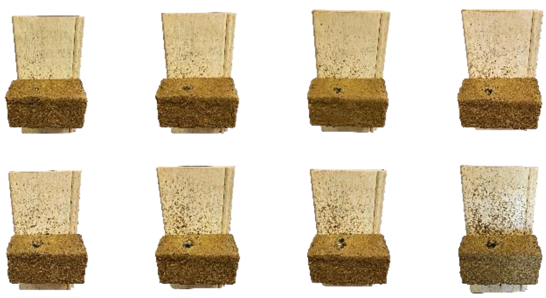
* Note: In the sample 'Albumen: solid' a pebble is showing at the drip spot.
The pebble shows in the imagery as a dark spot, visually suggesting pitting. This, however, is not the case.

Round 3 - Regular

Round 3 - Cement



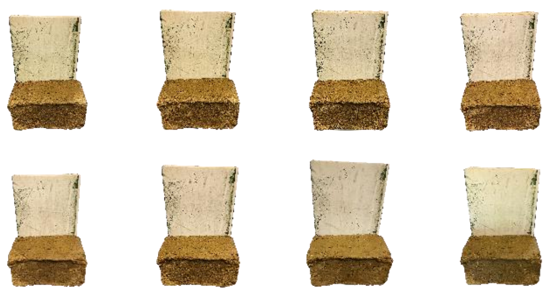
Round 3 - Sugar: 5%



Round 3 - Sugar: 2%

Round 3 - Albumen: Liquid

Round 3 - Albumen: Solid *



Interpretation – Drip test

To interpret the images given above, radar charts are made with the following categories:

1. Moment of first damage

Checking intervals: 1 hour – 2 hours – 3 hours – 4 hours – 5 hours – 6 hours – 8 hours – 24 hours

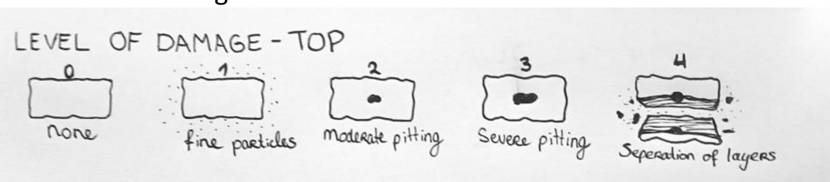
2. Weight difference

Measured before start of testing and after oven drying at end of testing.
Expressed in percentage of starting weight, given that every sample has a different starting weight.

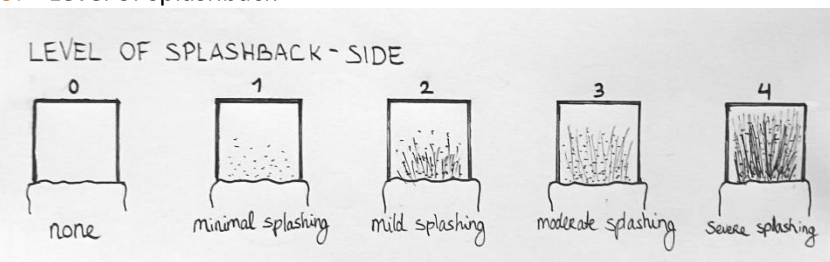
3. Depth of pitting

Measured at end of testing.
Expressed in centimetres of pitting, as seen from sample surface level.

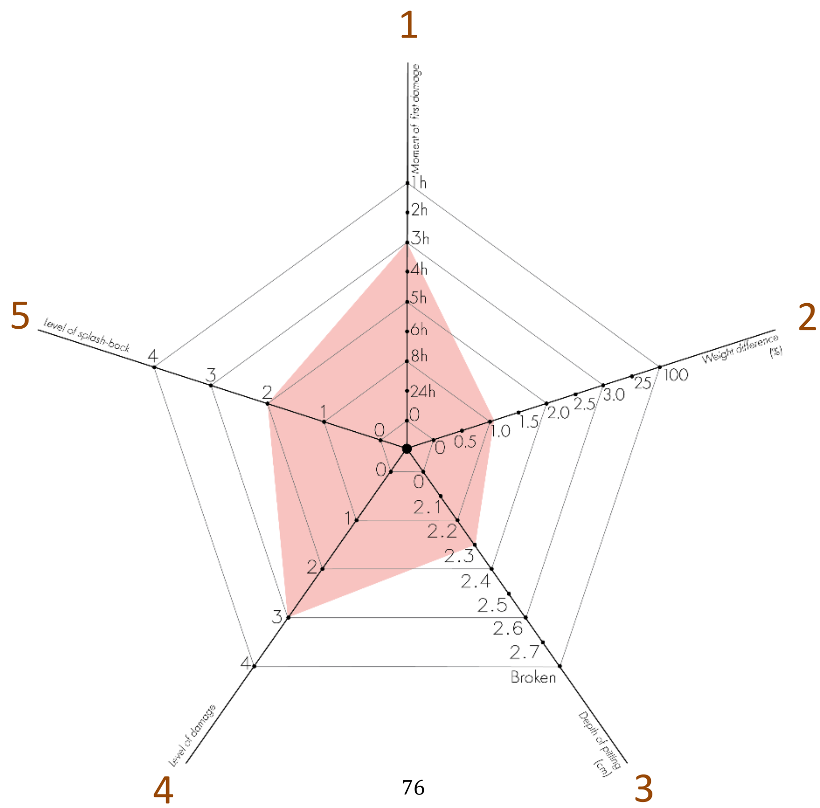
4. Level of damage



5. Level of splashback



Example result chart



Overview results – Drip test

As can be seen in *table 10*, marked in green, only the samples containing albumen sustain no damage in the drip test. This means they potentially have a level of resistance against consistent minimal water damage required to implement the material for structural use.

Sample type	Individual scores	Total scores	Moment of total dissolving	Rank
Regular 1	32	90	6h	5
Regular 2	29		*n/a*	
Regular 3	29		5h	
Cement 1	7	17	*n/a*	2
Cement 2	6		*n/a*	
Cement 3	4		*n/a*	
Sugar: 5% 1	21.5	61.5	*n/a*	4
Sugar: 5% 2	20		*n/a*	
Sugar: 5% 3	20		*n/a*	
Sugar: 2% 1	16	58.5	*n/a*	3
Sugar: 2% 2	23		*n/a*	
Sugar: 2% 3	19.5		*n/a*	
Albumen: liquid 1	0	0	*n/a*	1
Albumen: liquid 2	0		*n/a*	
Albumen: liquid 3	0		*n/a*	
Albumen: solid 1	0	0	*n/a*	1
Albumen: solid 2	0		*n/a*	
Albumen: solid 3	0		*n/a*	

Table 10 - Overview results – drip test

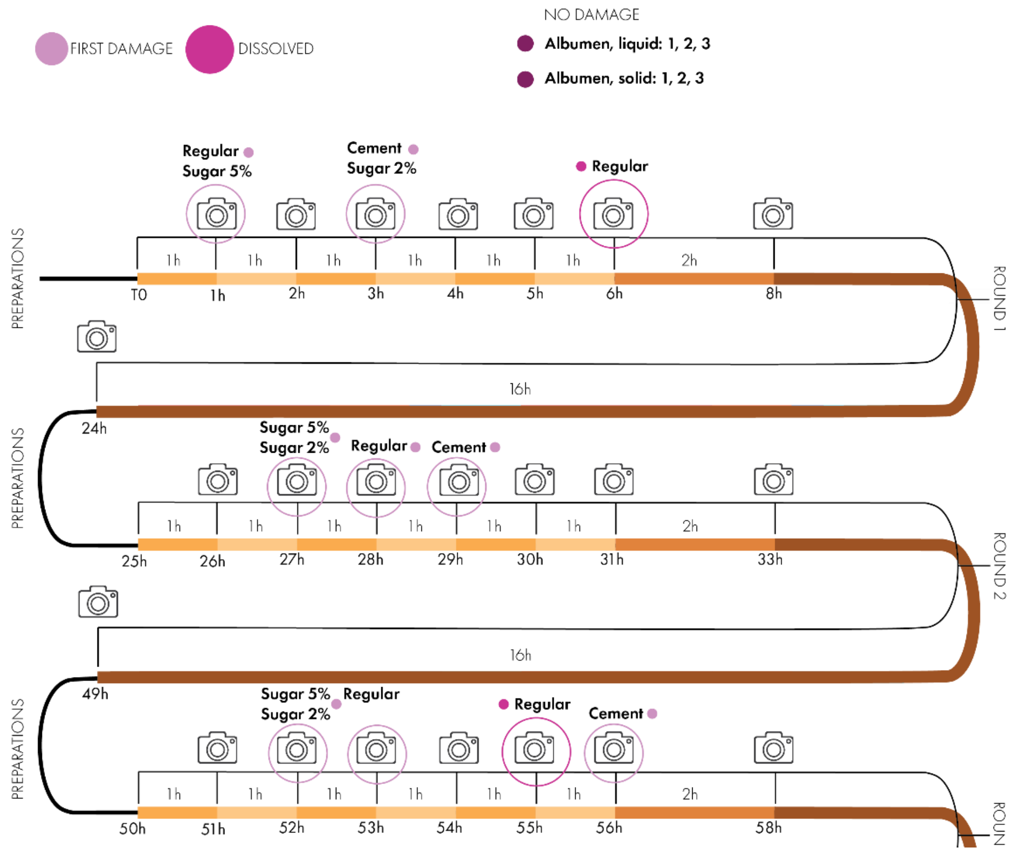


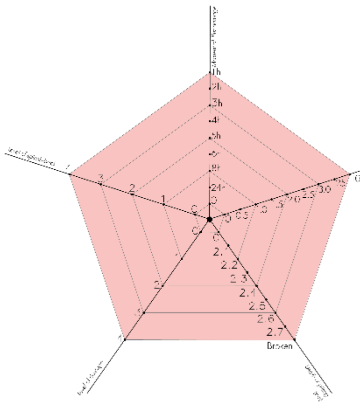
Fig. 43 – Moments of observed damage

Overview final damage – drip test

See Appendix 16. Drip test – Results, for detailed images.

Regular

1



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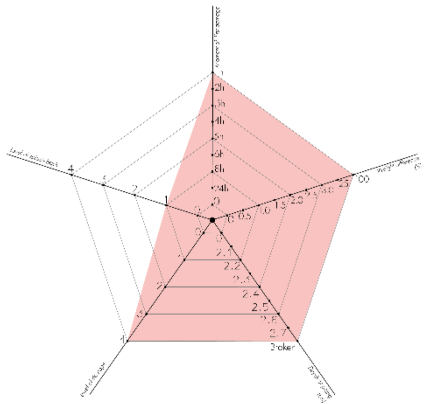

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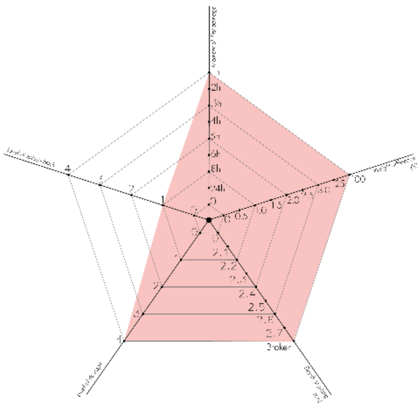
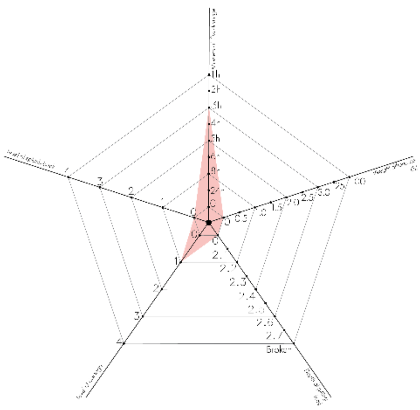


Cement

1



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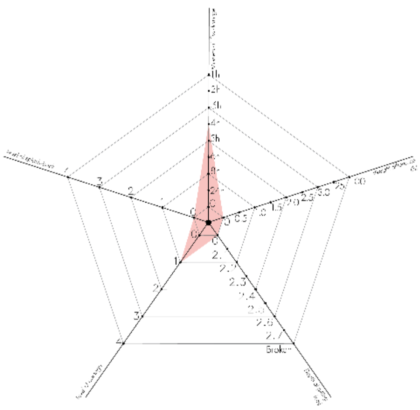

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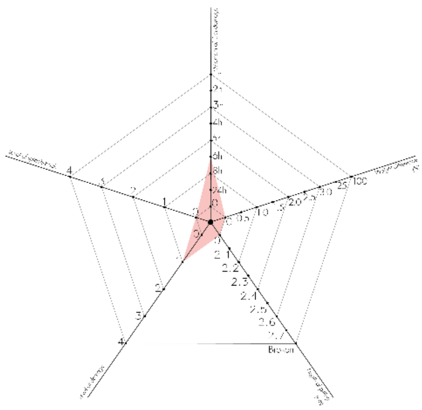
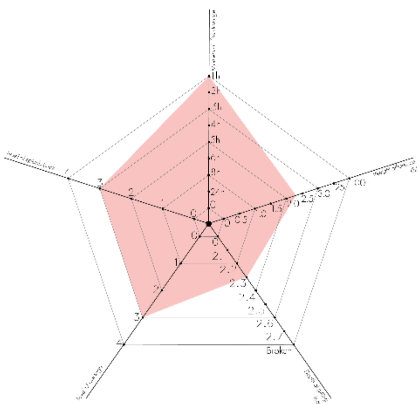
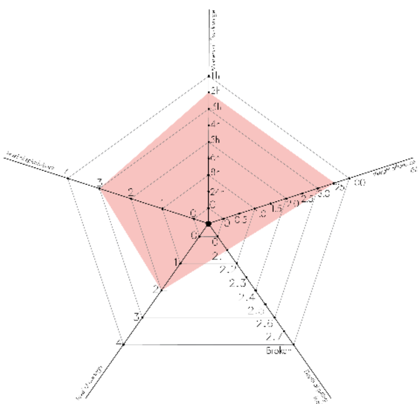


Sugar: 5%

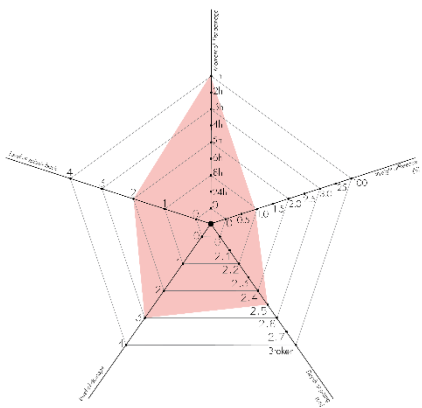
1



2

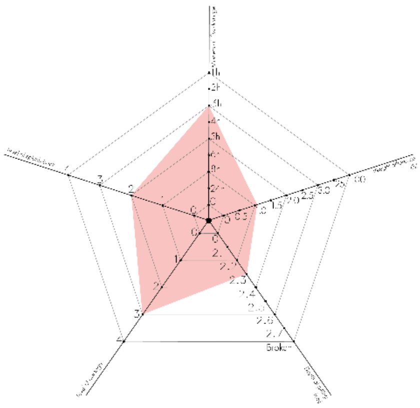


3

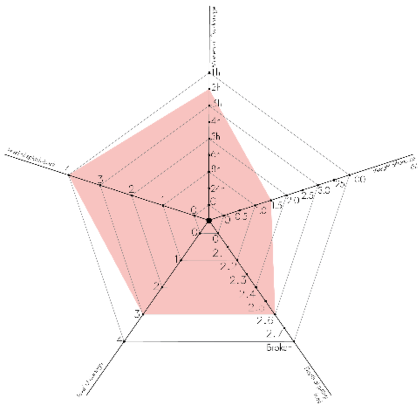


Sugar: 2%

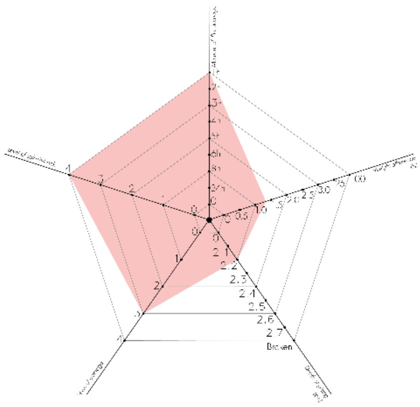
1



2

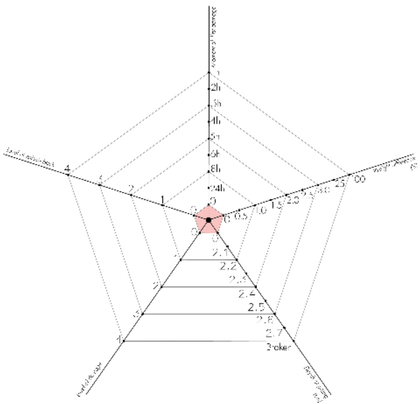


3



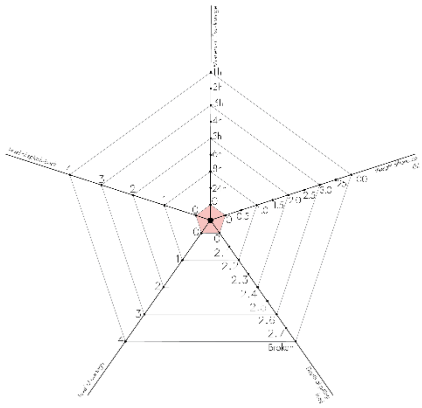
Albumen: liquid

1, 2, 3



Albumen: solid

1, 2, 3



4.3.2. Spray test

Execution – Spray test

Requirements

Fig. 44 - Shower head

- Test location
  Note 1: location needs to allow water drainage.
  Note 2: sheltered space, preventing test interruption due to wind
- Spraying shower head
  Diameter: 80mm.
  Amount of spray nozzles: 52 + middle part.
  Attachment: shower head parallel to sample.
- Sample stand
  Note 1: the stand needs to allow water drainage.
  Note 2: for this test, an oven rack was used.
- Measuring jug
  Range: minimum 1.5L.
  Precision: 100ml.
- Low temperature oven
  Temperature: 110 degrees Celsius.

Desired result

The desired result of the test is a sample comparison before and after test conduction, noting the weight reduction and visual changes. This is an indication of the level of resistance against heavy rainfall (Norton, 1997).

Test process

Fig. 45 - Spray test set-up

1. Prepare samples; labelling, weighing, recording results.
   6 sample types: 2x regular, 2x cement, 2x albumen liquid,
   2x albumen solid, 2x sugar 2%, 2x sugar 5%
2. Start water stream from shower head.
3. Place measuring jug next to the sample stand.
4. While placing jug on sample stand, start stopwatch.
   Note 1: place jug centred under shower head.
5. Pauze stopwatch when the jug contains 1L of water.
6. Adjust flow rate until desired speed is found.
   Note 1: flow rate should simulate heavy rainfall of test location.
   Note 2: for this test, the flow rate is 40L/h,
   simulating Dutch heavy rainfall (KNMI, n.d.).
   Note 3: the resulting required flow time for 1L is 90 seconds.
   Note 4: do not switch off the water, to guarantee constant flow rate.
7. Place sample on sample stand, record time *(T0)*.
   Note 1: place sample centred under shower head.
8. Check on test at set intervals.
   Intervals: (T0 + 20min) (T0 + 40min) (T0 + 60min)
   (T0 + 80min) (T0 + 100min) (T0 + 120min)
   a. Record damage visually.
   b. Record damage in writing.
   Note 1: do not touch or move sample.
9. Finish intervals of sample 1.
   Note 1: finishing step 1 to 8 concludes sample 1.
   Note 2: repeat for each sample type.

10. Finish samples of round 1.

Note 1: finishing step 1 to 9 concludes round 1.
Note 2: repeat for round 2.
Note 3: repeat for round 3.

18. At end of spray test, place surviving samples in the oven.

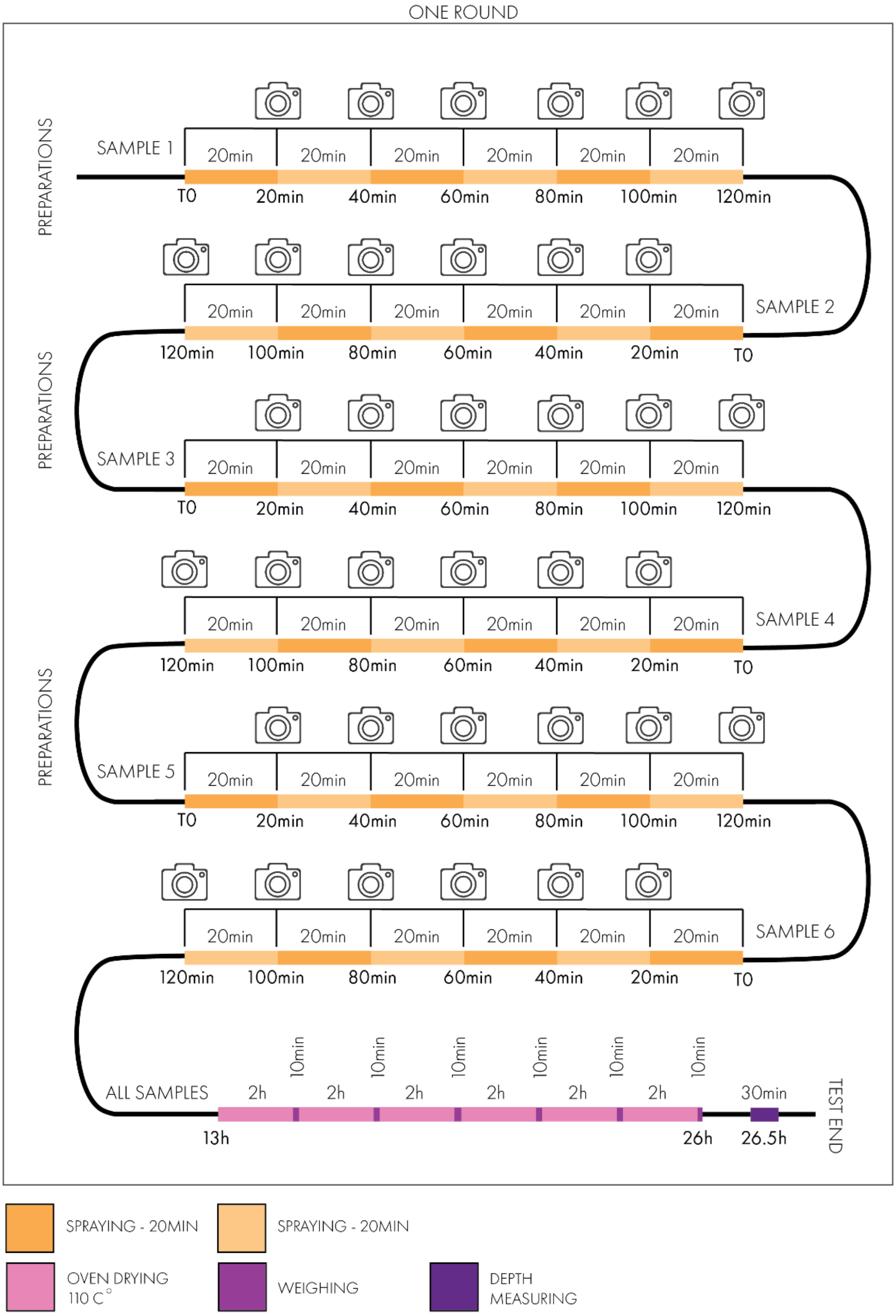
Temperature: 110 degrees Celsius.
Note 1: place samples on predetermined location.

11. Weigh samples every 2 hours, until consistent weight is reached.

Note 1: for this test, 12 hours of oven time was conducted.
Note 2: last weighing of samples for final results.

Fig. 46 - Drying of samples

Test timeline



Results – Spray test

The results of the spray test can best be described using imagery, the complete overview of each test interval can be seen in the illustrations below. The findings of these visual results are discussed per sample type in the table following each round overview. Any colour changes within the same tested sample are due to the passing of time, causing the movement of the natural light. The sample types lasting the whole duration of the tests without damage are 'Cement', 'Albumen: liquid' and 'Albumen: solid'. The checking is done at 8 intervals:

20 minutes – 40 minutes – 1 hour – 1 hour 20 minutes – 1 hour 40 minutes – 2 hours

See Appendix 17. Spray test – Images, for detailed images.

Spray test results – First round

Round 1 - Regular

Round 1 – Cement *

Round 1 - Sugar: 5%

Round 1 - Sugar: 2%

Round 1 - Albumen: Liquid

Round 1 - Albumen: Solid

Sample type	Damage	Level of damage	Weight difference	Rank
Regular	20 Min.	Disintegrated	- 1698 gram, 91%	4
Cement	n/a	None noticeable	n/a	1
Sugar: 5%	20 Min.	Pitting	- 235 gram, 12%	3
Sugar: 2%	1 Hour	Pitting	- 358 gram, 19%	2
Albumen: liquid	n/a	None noticeable	n/a	1
Albumen: solid	n/a	None noticeable	n/a	1

Table 11 - Overview results - spray test, round 1

Spray test results – Second round

Round 2 - Regular

Round 2 – Cement *

Round 2 - Sugar: 5%

Round 2 - Sugar: 2%

Round 2 - Albumen: Liquid

Round 2 - Albumen: Solid

Sample type	Damage	Level of damage	Weight difference	Rank
Regular	20 Min.	Disintegrated	- 1855 gram, 99%	4
Cement	n/a	None noticeable	n/a	1
Sugar: 5%	20 Min.	Severe pitting	- 186 gram, 10%	3
Sugar: 2%	40 Min.	Severe pitting	- 186 gram, 10%	2
Albumen: liquid	n/a	None noticeable	n/a	1
Albumen: solid	n/a	None noticeable	n/a	1

Table 12 - Overview results - spray test, round 2

As can be seen in *tables 11 & 12*, marked in green, the sample types ‘cement’, ‘albumen: liquid’, and ‘albumen: solid’ show no signs of damage due to the spray test. This means they potentially have a level of resistance against heavy rainfall necessary to use the material for structural use.

** There are no visible changes at any of the time intervals for the visual degradation of the cement sample. Following this set of images, when there is no noticeable damage, only the first and last interval are shown.*

Overview results – spray test

The observed progression of the sample damage as a result of the spray test can be categorised into two categories; the type of damage and the level of damage, *see figure 47*. Other damage typologies, like decreased structural properties, were not found. For each sample type, these two categories can be visualised for the duration of the test. When no damage was observed, the samples are left out of the consideration. This results in the following images.

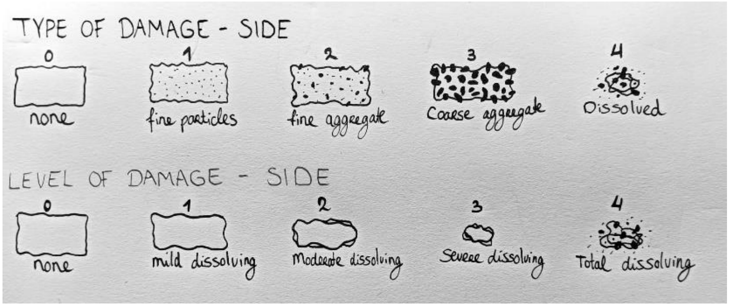
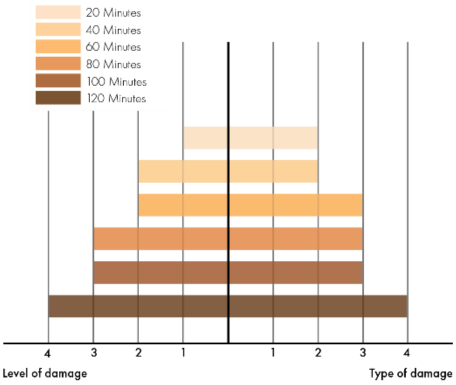


Fig. 47 - Visualisation of damage

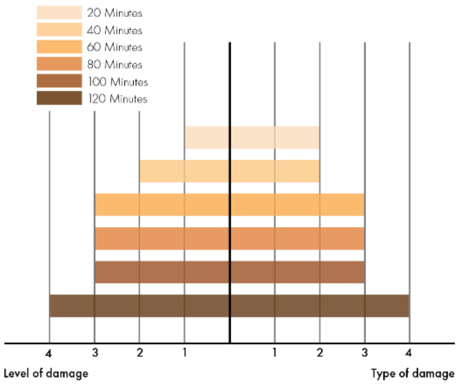
Round 1 - Regular

Sample type: Regular
Round number: 1



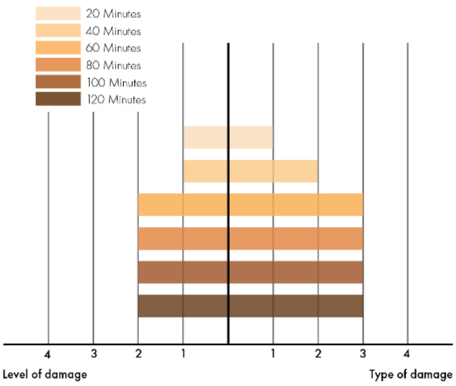
Round 2 - Regular

Sample type: Regular
Round number: 2



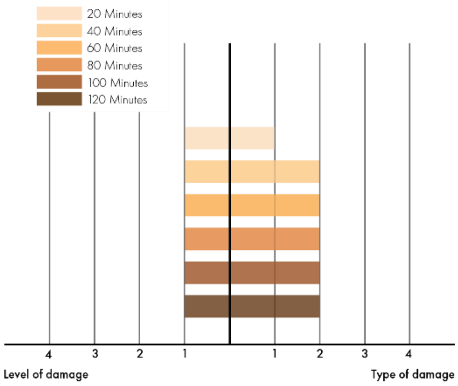
Round 1 - Sugar: 5%

Sample type: Sugar, 5%
Round number: 1



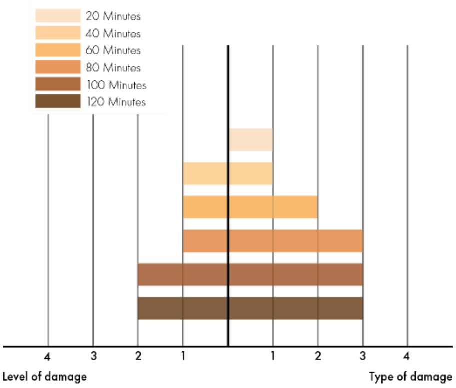
Round 2 - Sugar: 5%

Sample type: Sugar, 5%
Round number: 2



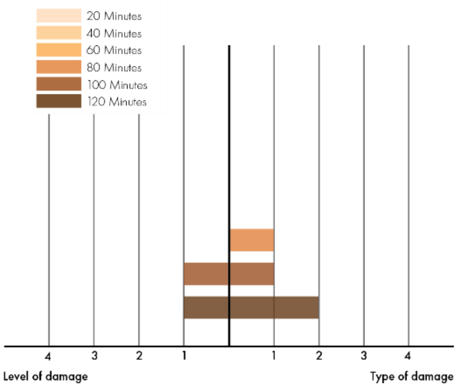
Round 1 - Sugar: 2%

Sample type: Sugar, 2%
Round number: 1



Round 2 - Sugar: 2%

Sample type: Sugar, 2%
Round number: 2



4.3.3. Moisture absorption test

Execution – Moisture absorption test

Requirements

- Container water submerging
  Label top horizontal axis: sample number.
  Label bottom horizontal axis: sample type.
- Scale
  Range: minimum 2.5kg.
  Precision: 1g.

Sample number

Sample type

Fig. 48 - Container

Desired result

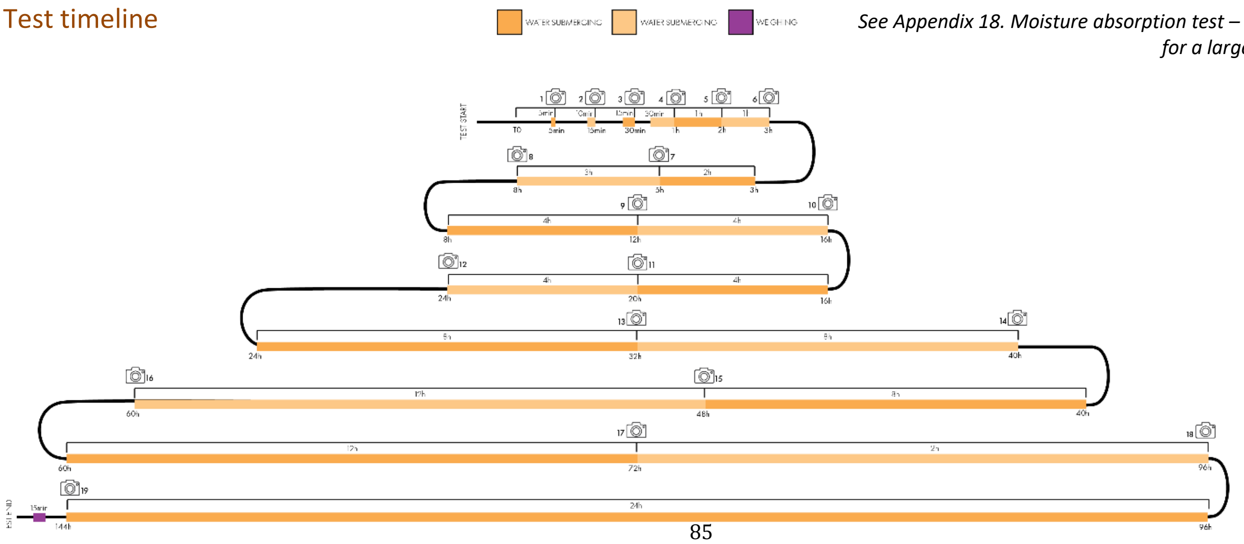
The desired result of the test is a sample comparison before and after test conduction, noting the weight increase and visual changes. This is an indication of the potential moisture absorption of the material, predicting possibly harmful swelling of constructions (Minke, 2008).

Test process

1. Prepare samples; labelling, weighing, recording results.
   6 sample types: regular, cement, albumen liquid, albumen solid, sugar 2%, sugar 5%
2. Place samples in container.
   Note 1: place samples on predetermined location.
3. Fill container with water *(T0).*
   Note 1: hit side of container with water, never directly on the samples.
   Note 2: water level 10cm above top of samples.
4. Check on test at set intervals.
   Intervals: (T0 + 5min) (T0 + 15min) (T0 + 30min) (T0 + 1h) (T0 + 2h) (T0 + 3h) (T0 + 5h)
   (T0 + 8h) (T0 + 12h) (T0 + 16h) (T0 + 20h) (T0 + 24h) (T0 + 32h) (T0 + 40h)
   (T0 + 48h) (T0 + 60h) (T0 + 72h) (T0 + 96h) (T0 + 144h)
   a. Record damage visually.
   b. Record damage in writing.
   Note 1: do not touch or move samples.
   Note 2: do not move the container for the entirety of test duration.
5. At test end, remove surviving samples from the container *(T + 144h).*
   Note 1: do not hold samples using pinch grip, hold samples on long sides, using flat hands.
6. Weighing surviving samples; final results.

Test timeline

See Appendix 18. Moisture absorption test – Timeline, for a larger image.



Results – Moisture absorption test

The results of the moisture absorption test can best be described using imagery, the complete overview of each test interval can be seen in the illustrations below. The findings of these visual results are discussed per sample type in the table following the overview. The sample types lasting the whole duration of the test are 'Cement' and 'Albumen: solid'.

See Appendix 19. Moisture absorption test – Images, for detailed images.

0 - Start

1 - 5 minutes

2 - 15 minutes

3 - 30 minutes

4 - 1 hour

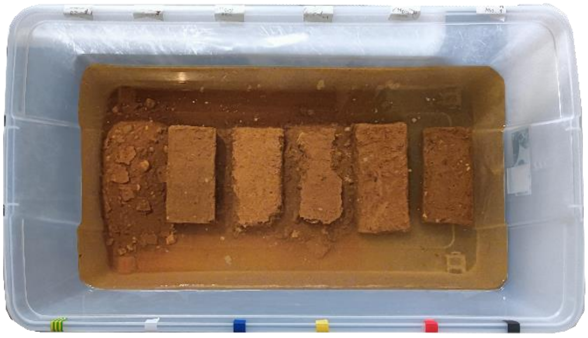
5 - 2 hours

6 - 3 hours

7 - 5 hours

8 - 8 hours

9 - 12 hours



10 - 16 hours

11 - 20 hours

12 - 24 hours, 1 day

13 - 32 hours

14 - 40 hours

15 - 48 hours, 2 days

16 - 60 hours

17 - 72 hours, 3 days

18 - 96 hours, 4 days

19 - 144 hours, 6 days

Sample type	Damage	Shape retention	Level of damage	Weight difference	Rank
Regular	5 Minutes	No	Disintegrated at 1 hour mark	n/a	5
Cement	n/a	Yes	None noticeable	+87 gram → 4,7%	1
Sugar: 5%	2 Hours	No	Disintegrated at 96 hour mark	n/a	4
Sugar: 2%	8 Hours	No	Disintegrated at 16 hour mark	n/a	4
Albumen: liquid	40 Hours	Yes	Severely cracked, no structural integrity	n/a	3
Albumen: solid	40 Hours	Yes	Hairline cracks, lessened structural integrity	+118 gram → 6,2%	2

Table 13 - Overview results - moisture absorption test

As can be seen in *table 13*, marked in green, only the samples containing albumen and the sample containing cement kept their shape during the moisture absorption test. This means they potentially have a level of resistance against long-term water damage required to perform structurally during longer periods of unintended contact with water. When removed from the container, the sample containing liquid albumen (indicated in red in *table 13*) disintegrated, indicating lower material performance in comparison to cement and dehydrated albumen.

Additionally, as can be seen in *table 13*, the samples containing albumen both sustain damage around the 40 hour submerging mark. This indicates a potential for material re-use, as the mixture returns to its original unbonded state. This cannot be observed in the sample using cement, thus preventing potential material re-use, making this a less sustainable binder variation (Zuiderveen et al, 2023).

4.3.4. Freeze and thaw test

Execution – Freeze and thaw test

Requirements

- Freezer
  Temperature: -10 degrees Celsius.
  Label shelves/drawers: sample type & number.
- Closable container: defrosting
  Label horizontal axis: sample type.
  Label vertical axis: sample number.
- Spray bottle: misting
- Absorbent material
  For this test, 6 layers of absorbent towel fabric were used.
- Scale
  Range: minimum 2.5kg.
  Precision: 1g.
- Weighted brush
  Weight brush: 224g.
  Added weight, splitting wedge: 2kg.
  Total weight: 2.224kg.
- Low temperature oven
  Temperature: 110 degrees Celsius.

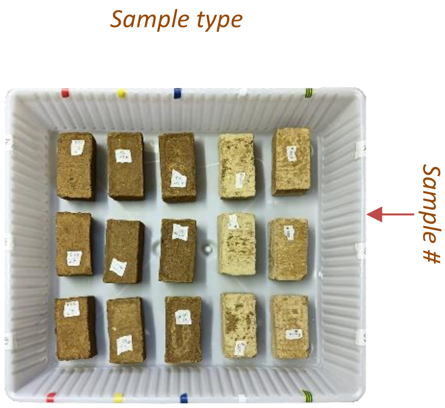
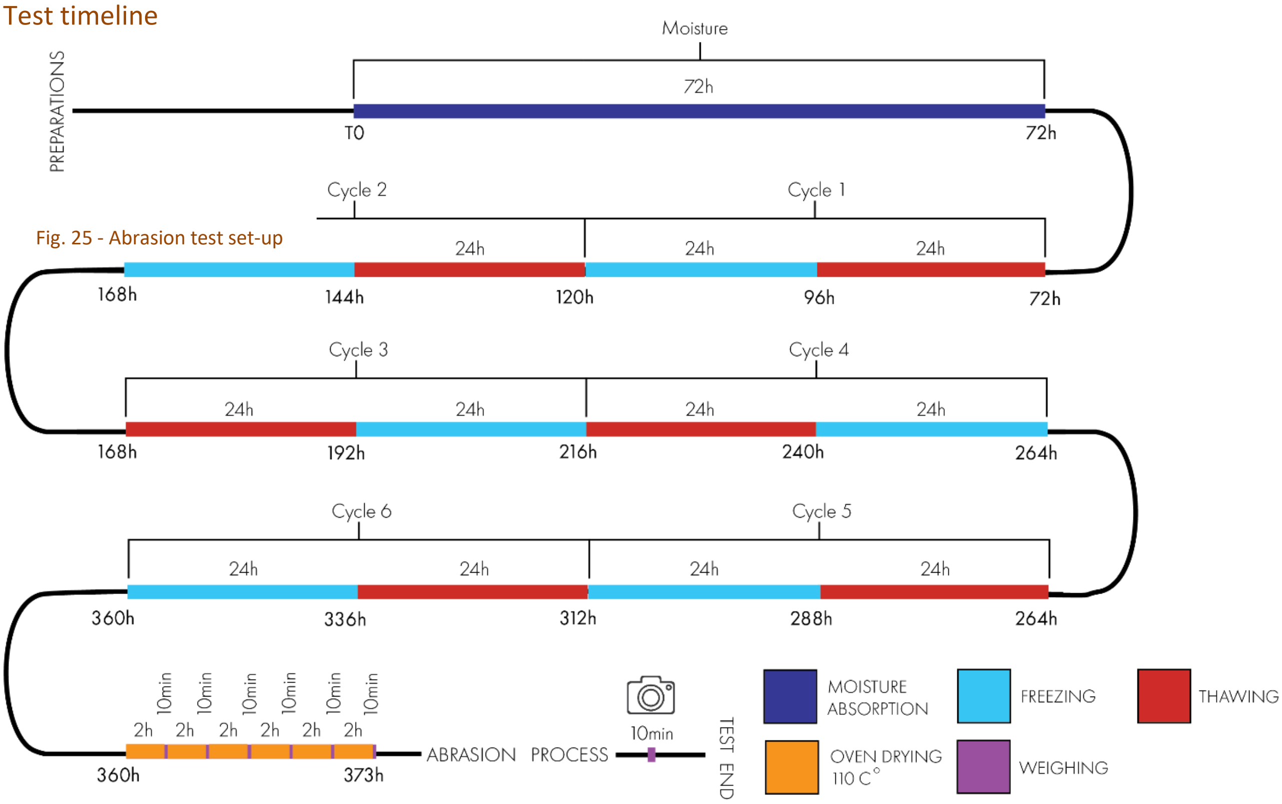


Fig. 49 - Defrosting container

Fig. 50 - Weighted steel brush

Test timeline



Desired result

The desired result of the test is a sample comparison before and after test conduction, noting the weight reduction and visual changes over time. This is an indication of the level of frost resistance, predicting possible damage behaviour in climates with harsh winters (Norton, 1997).

Test process

1. Prepare samples; labelling, weighing, recording results.
   6 sample types: 3x regular, 3x cement, 3x albumen liquid,
   3x albumen solid, 3x sugar 2%, 3x sugar 5%
2. Mist container with spray bottle.
   Note 1: cover all surfaces, including the lid of the container.
3. Place samples in container.
   Note 1: place samples on predetermined location.
4. Close container *(T0)*.
   Note 1: replenish moisture as needed at intervals of 2 hours.
5. Wet the absorbent material *(T0 + 72h)*.
6. Place absorbent material in the freezer *(T0 + 72h)*.
7. Place samples in the freezer *(T0 + 72h)*.
   Note 1: place samples on predetermined location.
8. Mist container with spray bottle *(T0 + 96h)*.
   Note 1: cover all surfaces, including the lid of the container.
9. Move samples from the freezer to the defrosting container *(T0 + 96h)*.
   Note 1: place samples on predetermined location.
10. Close container *(T0 + 96h)*.
    Note 1: replenish moisture as needed at intervals of 2 hours.
11. Defrost samples for 24 hours *(T0 + 120h).*
    Note 1: finishing step 1 to 11 concludes cycle 1.
    Note 2: repeat for cycles 2 till 6.
12. At the end of freeze and thaw cycles, place samples in the oven.
    Temperature: 110 degrees Celsius.
    Note 1: place samples on predetermined location.
13. Weigh samples every 2 hours, until consistent weight is reached.
    Note 1: for this test, 12 hours of oven time was conducted.
14. Removal of damaged areas samples; abrasion process.
    a. Place weighted brush on wedged in sample, bottom side 1.
    b. Move brush from bottom to top and back down.
       Note 1: hold brush with one hand on each side.
       Note 2: attempt to move the brush without added force.
    c. Repeat up-down movement 10 times.
       Note 1: 10 movement times = one cycle of abrasion.
    d. Repeat cycle of abrasion 3 times for all 6 sides.
       Note 1: abrasion cycle on 'left edge – centre – right edge' of each side.
       Note 2: 18 cycles of abrasion per sample.
    e. Repeat total cycles of abrasion on each surviving sample.

12. Collect final results.
    a. Weighing samples.
    b. Record damage visually.
    c. Record damage in writing.

Fig. 51 - Freeze and thaw test set-up

Fig. 52 - Absorbent material

Fig. 53 - Drying of samples

Fig. 54 - Abrasion set-up

Results – Freeze and thaw test

The results of the freeze and thaw test can best be described using imagery, the complete overview of each sample type can be seen in the illustrations below. The findings of these visual results are discussed per sample type in the table following the overview. The sample types lasting the whole duration of the test with minimal damage are ‘Cement’, ‘Sugar: 2%’, ‘Albumen: liquid’, and ‘Albumen: solid’.

Regular, no abrasion – Top of sample

Regular, no abrasion – Side of sample

The regular samples, with no added binder, freeze to be fully attached to the absorbent material. Because of this, removing the samples for thawing results in a high amount of damage. As can be seen in the images of ‘regular, no abrasion’, large chunks of material are missing around the corners. To minimise damage due to excessive force needed for removal, the ‘regular’ samples are allowed to defrost for one hour before removal of the absorbent material. This is contrary to the other samples, which can (and are) removed immediately upon removal from the freezer. After one hour, the material is not yet defrosted enough to allow for excessive moisture absorption in the samples from thawing.

Regular – Top of sample

Regular – Side of sample

After complete drying, the ‘regular’ samples are still fragile. This results in a large amount of material being removed during the abrasion of the samples. This material is mostly fine particles and small pebbles. Part of the samples suffer of separation of the rammed layers, resulting in further material reduction. This material is mostly larger chunks, breaking off according to damage lines.

Cement – Top of sample

Cement – Side of sample

Sugar: 5% – Top of sample

Sugar: 5% – Side of sample

Sugar: 2% – Top of sample

Sugar: 2% – Side of sample

Albumen: Liquid – Top of sample

Albumen: Liquid – Side of sample

Albumen: Solid – Top of sample

Albumen: Solid – Side of sample

Sample type	Level of damage	Weight difference	Rank
Regular, Before abrasion	Complete breakage, separation of layers, loss of corners	- 197 gram → 10,5% - 871 gram → 46,6% - 155 gram → 8,3%	6
Regular, After abrasion	Breakage, separation of layers, removal of deeper laying fine sand particles and fine pebbles, large pebbles at the new surface level	- 524 gram → 28,0% - 1048 gram → 55,9% - 402 gram → 21,5%	
Cement	Fragile edges before abrasion, removal of surface level fine sand particles, small pebbles at the new surface level	- 91 gram → 4,8% - 41 gram → 2,2% - 84 gram → 4,5%	4
Sugar: 5%	Loss of structural coherence during thawing, complete breakage, removal of surface level fine sand particles, small pebbles visible on original surface level	- 86 gram → 4,5% - 145 gram → 7,5% - 145 gram → 7,5%	5
Sugar: 2%	Loss of structural coherence during thawing, discoloration on original surface level	- 55 gram → 2,9% - 44 gram → 2,3% - 51 gram → 2,7%	2
Albumen: liquid	Discoloration on original surface level, more fragile compared to pre- test samples (see abrasion test)	- 24 gram → 1,3% - 30 gram → 1,6% - 24 gram → 1,3%	1
Albumen: solid	Discoloration on original surface level, more fragile compared to pre- test samples (see abrasion test)	- 75 gram → 3,9% - 61 gram → 3,2% - 66 gram → 3,5%	3

Table 14 - Overview results - freeze and thaw test

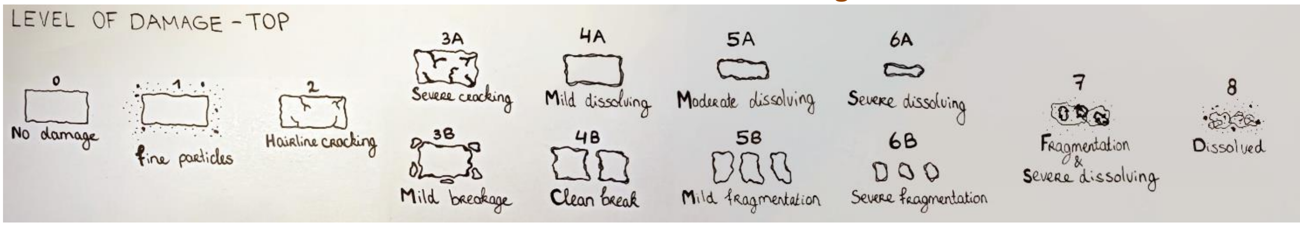
As can be seen in *table 14*, marked in green, the samples containing are ‘Cement’, ‘Sugar: 2%’, ‘Albumen: liquid’, and ‘Albumen: solid’ survived freeze and thaw test with minimal damage: less than 5% material loss. This means they potentially have a level of resistance against frost required to use the material for structural use.

However, a few of the samples of the types ‘Sugar: 2%’ become very tacky during the thawing process and are fully pliable in this stage. Therefore, these samples are most likely not viable for use in climates including frost seasons. In *table 14*, these are marked in red.

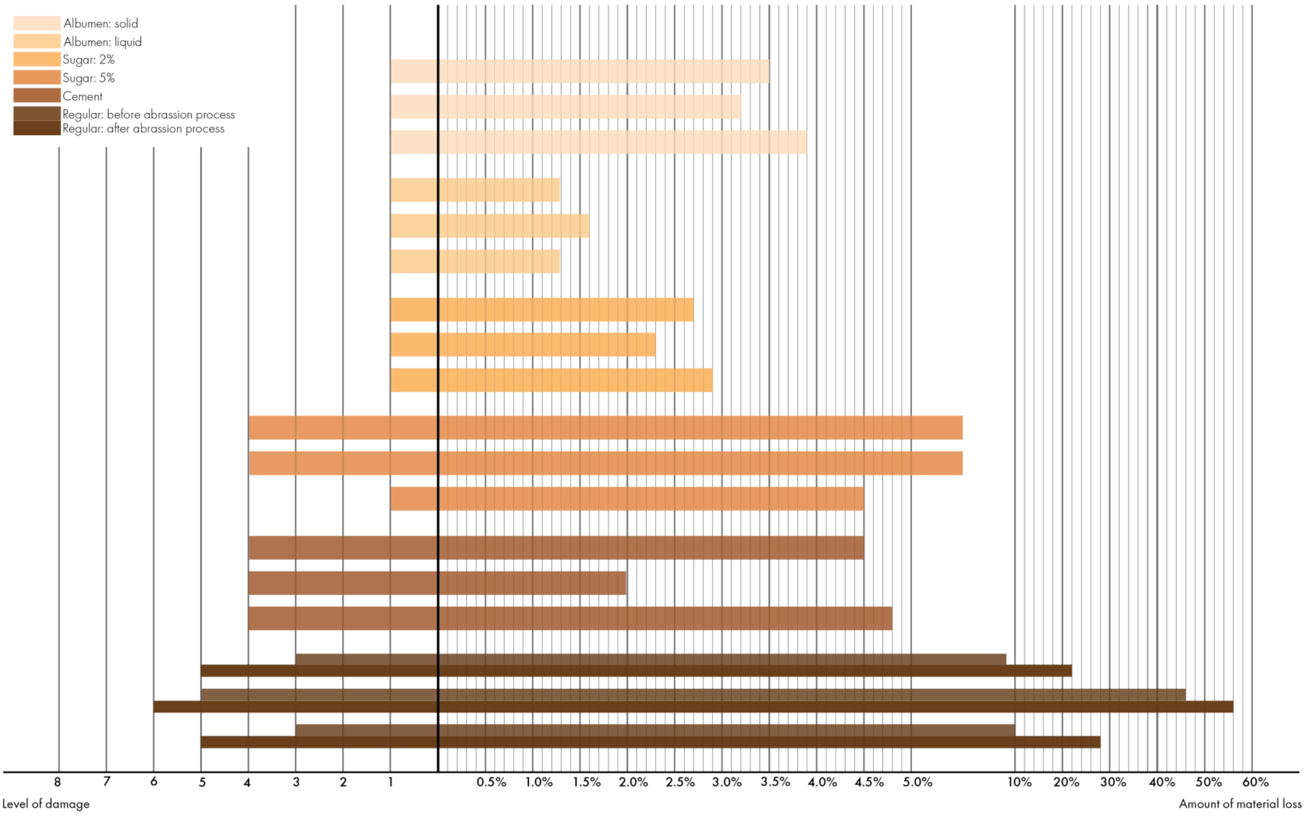
Overview results – Freeze and thaw test

The observed damage to the samples, as a result of the freeze and thaw test, can be categorised into two categories; the visual level of damage and the percentual loss of material. Other damage typologies were not consistently found for each sample type. These two categories of observed damage can be visualised for all samples. This results in the following image.

Classification of level of damage



Visualisation of sample damage



See Appendix 20. Freeze and thaw test – Results, for a larger image.

5. Discussion

5.1. Results

Rammed earth mixture

The chosen rammed earth mixture has a large effect on the sample performance. This is due to the undefined nature of rammed earth. All sources (Houben & Guillaud, 1994) (Minke 2000) (Dethier, 2020) (HiveEarth, n.d.) agree that rammed earth consists of fine sand particles, larger sand particles, fine aggregates, and larger aggregates. Additionally, a binding force is added in the form of clay, loam, silt, or a mixture of these. However, none of the authors give an exact 'recipe' for the composition of this mixture.

The composition is traditionally, and currently, based on the locally available material sources. An example can be the German use of broken roof tiles or alternative construction rubble as larger aggregates (GOLEHM, n.d.) instead of the common use of pebbles and rocks. Moreover, Nortwestern European historic rammed earth compositions make use of river loam, whereas for example Asian and African constructions make use of iron rich clay (Dethier, 2020).

On top of that, even in the Benelux there are commonly available variations of rammed earth mixtures, incorporating different loam materials. The assumption can be made that the wide ranges in material mixtures also result in wide ranges of material behaviour. This assumption can be continued to include a supposed wide variety of visual and tactile difference (Norton, 1997). More research is needed to truly determine the influence of the mixture composition on the material properties and structural behaviours of rammed earth. As binders interact with the available soils and clays (Minke, 2000), it can be assumed that the binder performance is depended on the composition of the rammed earth mixture used for construction. Additional research is required into the effects of varying clay or loam types on the performance of binders in rammed earth mixtures.

Binder types

The considered binders consist of sugar beet variations and chicken egg variations. Both binder sources are traditionally used in the food industry for human consumption. This means the intended research aim of using waste-stream produced binders was not achieved. Furthermore, the production of chicken eggs requires large scale animal farming. Both of these factors lead to a question of morality being raised: is it acceptable for the built environment to use valuable nutritional resources?

To attempt to combat the morality of this choice, alternative ways of achieving the use of waste streams has been considered. For the use of granulated sugar, no waste streams were determined. For the use of albumen, several potential waste streams were identified. Sources of eggs unsuitable for human consumption are:

- Production sector – Eggs damaged during the farming process
- Retail sector – Eggs past their expiration date or damaged during shipping
- Agricultural sector – Eggs discarded during the breeding process of chickens

In the production sector as well as in the retail sector, usable waste-streams could not be determined through several conducted interviews. The production sector indicated that damaged eggs are used in the production of processed foods. The retail sector indicated that their supply of eggs is tracked using their 'best by - date', the date before which eggs should be sold. Before this date is reached, the retailers donate the eggs to local foodbanks.

No conclusion could be drawn on the final egg source, the agricultural sector. A potential lead for further research is in-ovo sexing companies, which discard eggs on a large scale during their egg sexing processes (Kayadan & Uzun, 2023).

Findings

The tests conducted in this research are based on standardised rammed earth testing methods (Houben & Guillaud, 1994) (Minke, 2000) (Norton, 1997). These tests provide intended findings, to be judged against predetermined desired test outcomes. However, as discovered through application of said tests, most could not be executed as described. To overcome this, alternative test methods were devised and described.

The results found with these new testing methods cannot be compared to predetermined guidelines, as they are not (yet) used for other material explorations. No standard of expected test results can be given. For this reason, the only true conclusion that can be drawn from the devised testing methods is the potential for future test standardisation, based on iterations of the proposed testing methods.

The test results of this research need to be regarded as hypotheses for further research, instead of definitive findings. The main finding of this research, the material score of *figure 16*, can be seen as encouragement to continue to further investigate the use of dehydrated albumen as a binder in rammed earth construction.

Moreover, the results of the applied testing methods might not illustrate an accurate performance of the material. There are currently too many undefined factors to guarantee scientific replicability. This is the case for both the testing methods and the sample construction.

5.2. Methodology

Sample construction

The sample sizes used for testing was not specified in the considered literature. To formulate appropriate sizing, this research referred to the standard cube sizing used in mechanical compression tests, 15x15x15 cm, as explained by the staff of the Microlab at Civil Engineering. However, the drying time required for these samples was not feasible in the allotted research time. This required smaller samples to be made, speeding up the hardening process. The existing cube formworks got sized down to resemble brick-like blocks, measuring 8x15 cm. The height of the samples, 7cm, exists of 4 layers with equal weight, 500g, to ensure layering in the sample. Layering is an indicated potential weakness of rammed earth (Minke, 2000) The lack of available standardised sizing for rammed earth samples results in several discussion points. Firstly, the altered sample size prevents comparison to findings from previously conducted research, using either rammed earth or alternative construction materials. This narrows the potential use of the research findings. Secondly, the dimensions of the samples do not accurately represent rammed earth constructions.

Structural rammed earth consists of compacted layers approximately 10 centimetres in height (Houben & Guillaud, 1994). In the samples, average compacted layer height is 1.75cm, with a total height of 7cm. If one were to cut a block out of a structural rammed earth wall, with sizes equal to the sample sizing, there would be no layering of the material in said block. As friction between layers is one of the constructive forces of rammed earth construction, (Dethier, 2020), the samples potentially display a higher level of cohesion in comparison to true-to-size rammed earth constructions. Assuming this to be true, the results observed in the conducted tests would not translate to material behaviour of true-to-size construction. The lessened friction would make the material more susceptible to damage than the test results currently suggest.

Similarly, the sample size could have another big influence on the test results. Bigger samples have a smaller ratio of *'surface to volume'*. This difference in size could alter the speed of moisture absorption and the level of moisture penetration of samples. As rammed earth performance in part relies on the formation of capillary bridges inside the material (Minke, 2000), changes to the material behaviour in regards to moisture could be detrimental for accurate test results. If this hypothesis is true, the results observed in the conducted tests do not give an accurate representation of rammed earth behaviour. The altered formation of capillary bridges would make the material more susceptible to damage than the test results indicate.

Additionally, samples are tested individually. This means that no load is exerted onto the samples. As the research aim specifies the search for load-bearing capabilities of rammed earth, a discrepancy arises between the manner of test execution and the intended use of the material. Potentially, the constant compaction of the material aids in the structural performance of rammed earth. If this would be the case, the results observed in the conducted tests do not accurately describe the damage patterns of large-scale rammed earth constructions. The absence of the added load would make rammed earth less vulnerable to damage as the test findings imply.

Lastly, the test results can vary greatly depending on the quality of construction for each individual sample. Because the samples were produced by hand, using crude techniques, it is not guaranteed that each sample is representative for the overall material performance. There is no uniform level of compaction of the material, not even within each sample. This could be prevented by using pneumatic rammers, while also increasing the potential maximum material density (Minke, 2008). These steps would result in uniform samples with enhanced material properties, such as resistance to water and overall strength (Norton, 1997).

Testing methods

The tests in the literature are described in a matter that allow for a certain degree of scientific replication, but much is left to the interpretation of the reader. For example, in the drip test, a provisional set-up using a 'deep container' and a 'cotton string' are mentioned. The resulting drip rate greatly varies on the type and size of both the container and the string. Even more so, it was found that this method was not viable for accurate and consistent results and had to be fully altered to be performed. Another example is the spray test. Here, the required water pressure was described and the diameter of the shower head, but the resulting water impact cannot be determined given only these factors. For each individual test a new design is made, based on the tests described in literature.

Arguably, the performed testing could be optimised by narrowing the scope on the desired performance enhancement of only one aspect of the material (i.e. Either improved compressive strength OR frost resistance OR water resistance). This would allow for more elaborate testing methods. Preferred would be the use of mechanised standardised testing facilities, for high degrees of replicability.

Test validity

After having performed the newly devised tests, the validity of these tests can be argued. Even after alterations, the samples containing no binders often did not withstand all rounds of testing, reaching failure far before the test end. The hypothesis can be made that the original tests were devised to test the performance of stabilised rammed earth samples. Additionally, the literature mentions found test results being only a first indication of the material behaviour, calling attention to the possibility of true to size rammed earth constructions performing differently in-situ compared to the indicated performance of conducted tests (Houben & Guillaud, 1994) (Minke, 2000) (Norton, 1997).

A standardised set of testing for rammed earth samples, both with and without binders, is essential. These tests need to consider suitable sample sizing, to replicate material behaviour of full-scale rammed earth construction. This would allow all material developers to execute the same set of tests in a precise manner, thus producing results that can be universally compared. This would allow for the possibility of forming replicable conclusions regarding the material performance.

6. Conclusion

6.1. Testing

The overall performance of the samples can be determined by ranking their separate test performances, according to the results of the conducted tests. To organise these 'rankings', colours are assigned.

Ranking	6th	5th	4th	3rd	2nd	1st
Colour						

After determining the ranking of conducted tests, each binder material has a total accumulated score of performance. The best performing binder will have the lowest total score.

The various tests are organised using their chapter number and name. The impact test as well as the strength tests are excluded from the results, as no clear performance criteria can be formulated.

Sample type	4.2.1. Wetting and drying test	4.2.2. Abrasion test	4.2.3. Penetration test	4.2 Mechanical Characteristics Total Score
Regular	6	6	5	17
Cement	1	5	4	10
Sugar: 5%	5	4	6	15
Sugar: 2%	4	1	2	7
Albumen: liquid	3	2	3	8
Albumen: solid	2	3	1	6

Table 15 - Overview results – mechanical characteristics testing

Sample type	4.3.1. Drip test	4.3.2. Spray test	4.3.3. Moisture absorption test	4.3.4. Freeze and thaw test	4.3 Total Score	4. Total Score	Final Rank
Regular	5	4	5	6	20	37	5th
Cement	2	1	1	4	8	18	3rd
Sugar: 5%	4	3	4	5	16	31	4th
Sugar: 2%	3	2	4	2	11	18	3rd
Albumen: liquid	1	1	3	1	6	14	2nd
Albumen: solid	1	1	2	3	7	13	1st

Table 16 - Overview results – weathering testing

The final conclusion of the testing is that solid (dehydrated and powdered) chicken egg albumen shows the most promising material property changes in the conducted tests, compared to the alternative considered binders and binder percentages, *see table 16*. Moreover, for each test, samples with binders performed significantly better than samples without any binder, *see table 16*, proving the advantage of binder use.

6.2. Research questions

Main question:
How can the use of bio-based binders improve the material performance of rammed earth in Northwestern European building construction?

For determining potential improvement of rammed earth material performance, tests are conducted on samples containing various binder types; granulated beet sugar, chicken egg albumen, and cement. The binder percentages of interest for this research are '2% granulated beet sugar', '5% granulated beet sugar', 'liquid chicken egg albumen', and 'dehydrated chicken egg albumen' (also referred to as 'solid chicken egg albumen'). The samples that incorporated 5% cement are used for comparison, given the fact that cement is commonly used for material improvement of rammed earth.

The tested factors for improvement are resistance against fluctuating moisture levels, abrasion damage, penetration damage, impact damage, compressive damage, tension damage, penetrating water damage, flowing water damage, standing water damage, and frost damage. The amount of damage observed varied not only per binder type, but also per test type. Unless a specific material function is determined, there is no one binder material that continuously outperforms its counterparts.

However, samples with an incorporated binder continuously performed significantly better than samples without any binder. As can be seen in the ranking of the results in table 16, the use of the considered bio-based binders improved material performance in all conducted tests. The results thus show a clear potential for various categories of material improvement by implementing bio-based binders in rammed earth.

Sub questions:

1. What material property enhancements are possible for modern-day rammed earth construction?

   To enhance rammed earth material performance, changes can be made to the material plasticity, the material workability, the material strength, the material properties, or the drying process (Minke, 2008). To determine which enhancements are relevant for modern-day rammed earth constructions, it is necessary to refer to the problem statement. There is a current need for affordable, low energy, low emission, and recyclable building materials that can replace the common use of inorganic materials in the built environment. Fulfilling this need, by enhancing contemporary rammed earth material properties, allows for a reduction of the overall negative climactic impact of the built environment (Zuiderveen et al., 2023).

   The main hurdle for the implementation of rammed earth construction into the modern-day built environment can be described as a lack of compressive strength when measured against the current building norms (Dethier, 2020). This indicates that material enhancement requires a positive effect on compressive strength. In this research, material enhancement is attempted by implementing binders. In addition, perceived weaknesses for rammed earth construction in Northwestern Europe are related to ease of workability, water resistance, and resistance to freeze-thaw cycles (Minke, 2006). Although not technically a material enhancement, it is important to consider the need for recyclable contemporary construction materials. This is needed to further limit the negative climactic impact of the built environment (Zuiderveen et al., 2023). A suggested set of criteria for relevant rammed earth material performance enhancement, suitable for use in Northwestern Europe, is formulated in chapter 2.3.2. Criteria definition.

2a. What bio-based binders have been used in historic raw earth construction?
2b. What were their intended adjustments on raw earth material properties?

The historic bio-based binders used for raw earth construction can be divided in 7 different groups:

1. Animal derivatives | *2. Animal produced*
3. Plant based | *4. Ashes*
5. Oils | *6. Resins*
7. Gums

For each group, there is a vast number of examples available. Although incomplete, this research attempts to give an overview of historic bio-based binders, as can be seen in appendices 3 to 9. Further research can be conducted into completing and improving this overview.

This same principle is valid for discovering the historically intended adjustments on raw earth material properties. In appendices 3 to 9, the reason for implementation of each recorded binder is noted. However, for some binders, no intended adjustments could be found. The areas left blank in the appendices reflect this.

Further research into historic rammed earth constructions would provide answers for these knowledge gaps. By chemically analysing surviving historic rammed earth constructions, it is possible to determine the material compositions of the past (Zeng et al., 2008). Additionally, in areas where rammed earth construction is still a common practice, interviews can be conducted with local craftsmen. These craftsmen oftentimes hold generational knowledge that is not found in literature and is therefore at risk of being forgotten (Dethier, 2020).

3. What information from rammed earth history can be applied to the use of modern-day rammed earth?

Rammed earth is used as a construction method during and after times of largescale changes to society, such as wars or severe scarcities (Correia et al., 2011). Social ideologies regarding material sustainability are often formed as a response to these changes to society (Fissabre & Wilson, 2012). The current day need of the built environment is a reduction in energy consumption and harmful emissions (Rath, 2004), which in part can be achieved through material sustainability (Zuiderveen et al, 2023). This means that the modern-day search for a sustainable building material can be compared to similar searches during past time periods, where rammed earth was found to be a promising sustainable option for construction.

However, each rammed earth revival period is followed by the abandonment of the material in favour of industrialised construction materials (Jaquin et al., 2008). These industrialised materials are more accessible for use, as they follow standardisation guidelines and thus meet relevant building norms (Maravelaki-Kalaitzaki et al, 2023). To be able to successfully implement rammed earth into the current built environment, an effort should be made to form European building norms regarding the implementation of rammed earth: one for stabilised rammed earth and one for un-stabilised rammed earth (Fabbri & Morel, 2016). With said building norms in mind, rammed earth standardisation can be achieved. This would allow for cost and time effective rammed earth constructions (Rauch, 2020), making the material a valid alternative to common high-emission construction materials.

4. How can the performance of bio-based binders in rammed earth constructions be tested?

   To determine the performance of rammed earth mixtures, in this case containing bio-based binders, experiments must be conducted both during the fresh and hardened state of the rammed earth mixture. At the fresh state, the sensory experiences related to the material mixtures predict the performance of the material in the hardened state (Norton, 1997). After the hardened state, strength and durability testing determines the quantitative effect of the binder in question. This is done by constructing and comparing samples using the rammed earth mixture with and without the bio-based binders in question (Maravelaki-Kalaitzaki et al, 2023). Comparisons are made in the form of test results.

   Descriptions of the most frequently conducted testing methods can be found in most literature regarding the material performance of raw earth (Houben & Guillaud, 1994) (Minke, 2000) (Norton, 1997). For most of the tests performed in this research (apart from the shrink box test), the described testing methods could not produce a valid scientific result.

   Firstly, descriptions did not include all necessary information for test execution, like sample size or test set-up definitions. Secondly, found results did not fit the described expected results. Alterations to the testing methods needed to be made, in the form of altered execution or altered interpretation of the results. Even after alterations, the conducted tests were not entirely suitable for testing the samples containing no binders. The samples often did not withstand all rounds of testing, reaching failure far before the test end. Additionally, the literature mentions found test results being only a first indication of the material behaviour, calling attention to the possibility of true to size rammed earth constructions performing differently in-situ compared to the indicated performance of conducted tests (Houben & Guillaud, 1994) (Minke, 2000) (Norton, 1997).

   A standardised set of testing for rammed earth samples, both with and without binders, is essential. This would allow all material developers to execute the same set of tests in a precise manner, thus producing results that can be universally compared. This would allow for the possibility of forming replicable conclusions regarding the material performance.

5. Which bio-based binders can be implemented for possible material enhancement of modern-day rammed earth construction in Northwestern Europe?

Required enhancement of rammed earth material performance suitable for Northwestern Europe are formulated in chapter 2.3.2. Criteria definition. To find which bio-based binders can suit these needs, a matrix combining the criteria with the information on the historic binders described in literature is made in chapter 2.3.3. Matrix binders. A high material score in this matrix is hypothesized to illustrate the binder's potential of rammed earth material enhancement.

The historic bio-based binders with a high matrix score could all be suitable for implementation, yet not all are currently scientifically replicable, lacking necessary material definitions. There is potential for binders with a low matrix score to still be relevant for required material enhancement; not all information essential for material scoring can be found regarding all considered binders. With further research into historic binder uses, the findings of the matrix can be improved. The binders considered in this research are chicken egg variations and beet sugar variations. Of which, dehydrated chicken egg albumen shows the greatest potential for material enhancement of rammed earth construction for Northwestern Europe, see table 16.

6. How does the implementation of these bio-based binders in rammed earth mixtures affect rammed earth performance?

   To determine potential enhancements of rammed earth material performance, tests are conducted in this research on samples containing no binder as well as samples containing various binder types. The tested factors for improvement are resistance against fluctuating moisture levels, abrasion damage, penetration damage, impact damage, compressive damage, tension damage, penetrating water damage, flowing water damage, standing water damage, and frost damage. Enhancements of material performance, comparing samples with and without binders, could be observed for all of these factors. The results thus show a clear potential for various categories of material improvement by implementing bio-based binders in rammed earth.

7. How do rammed earth constructions using bio-based binders perform compared to those made with the commonly used cement binder?

   The samples containing 5% cement have an equal found 'material score', see table 16, to those containing 2% of granulated beet sugar. The 'material score' of cement mixture is surpassed by both liquid chicken egg albumen as well as dehydrated chicken egg albumen. Hypothetically, this would mean these bio-based binders perform better or equal to cement in long-term exposure to the elements during building life.

   However, not all conducted test are equally relevant for the performance of constructions in-situ. For example, the results of the penetration test have less influence on the potential building lifespan compared to the results of the spray test. Minor exterior damage can easily be repaired or prevented, while significant structural damage cannot. For an accurate comparison of potential in-situ material performance, prototypes containing both cement and alternative bio-based binders need to be conducted.

   Additionally, the moisture absorption test in chapter 4.3.3. proves that the samples with the considered bio-based return to their unbonded material state during long-term exposure to moisture, while the sample containing cement does not. Material mixtures containing bio-based binders can thus theoretically be re-used after end of life as raw material, while those with cement cannot.

6.3. Further research

6.3.1. Continuation graduation research

Although each test conducted in this research shows a first indication of material performance, none truly replicate the effect of constant exposure to the elements (Norton, 1997). It is therefore imperative to make samples, although preferably an in-situ prototype, that can be exposed to local weathering conditions over a longer time period. Only by conducting such practical research can the data necessary to predict final material performance be gathered, proving the relevance of the innovation.

As a continuation to this graduation research, a functional prototype can be constructed to find long-term weathering exposure test results. The suggested prototype, *see figure 56*, shows both in-situ façade walls (dimensioned to resemble structural rammed earth façades, at the bottom half of the prototype) as well as prefabricated rammed earth blocks for façade infill. To be able to determine the influence of the used loam mixture on the performance of the binder, a variety of coloured rammed earth mixtures should be used, *see figure 55*. Each material mixture containing the bio-based binder that performed best in this research; 1,25% dehydrated albumen powder.

Fig. 55 - Visualisation suggested rammed earth colour variation prototype

The proposed prototype testing consists of the implementation of moisture sensors at the centre of both wall functions, structural and infill, as well as core samples taken from both wall types. Additionally, sensory observations relating to weathering damage can be recorded during the life-span of the prototype.

A combination of available local weather data, as well as the data collected by the moisture sensors in the prototype, will hypothetically be able to show a relation between the moisture absorption into the material centre and the relative air humidity as a result of the implementation of dehydrated albumen powder.

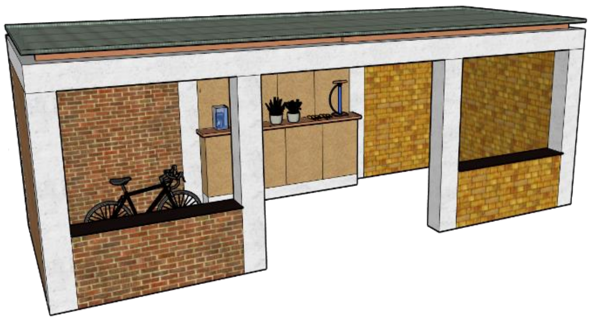


Fig. 56 – 3D visualisation suggested prototype

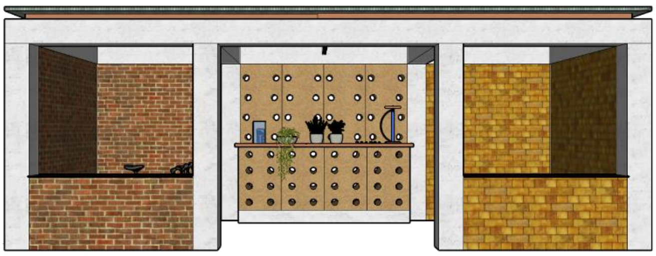


Fig. 57 - Visualisation core sampling of suggested prototype

The literature indicates (Dethier, 2020) (Minke, 2000) (Norton, 1997) that rammed earth constructions increase in strength and material performance over time, as a result of continued material compaction. The collected core samples, taken biannually over a duration of 4 years, can hypothetically show this increased compaction of the material over time. By studying the core sample composition using a microscope and testing the core samples for compressive strength using a hydraulic press, this behaviour can be observed.

Note: The design is based on a proposed prototype at The Green Village on the TU Delft campus. It exists of a wall that is 2.7 metres wide and 2.53 meters tall, placed in their open-air test location.

6.3.2. Suggested further research

Further research needs to be conducted on various topics related to rammed earth constructions to be able to optimise material performance. To be able to implement existing knowledge relating to rammed earth construction into the modern-day built environment, additional research into historic earthen architecture and construction methods is required. Similarly, in-depth research into historic bio-based binder use can provide more solutions for rammed earth material enhancement. To acquire contemporary knowledge on rammed earth, further research can be conducted on various relevant topics; material mixtures, testing methods, building norms, and end-of-life of the material.

History rammed earth

Locating and examining surviving Northern European rammed earth constructions allows for an improved understanding of the historic use of rammed earth and its variations regarding location (GOLEHM, n.d.). Additionally, in areas where rammed earth construction is still a common practice, interviews can be conducted with local craftsmen. These craftsmen oftentimes hold generational knowledge, which can be seen as oral history, that is not found in literature and is therefore at risk of being forgotten (Dethier, 2020).

History bio-based binders

The overview of historic bio-based binders given in this research is a first attempt at historic binder inventory, but further research is needed for completion of the data. This can be done in the form of further literature research as well as practical research. As an example, by chemically analysing surviving historic rammed earth constructions, it is possible to determine the material compositions of the past (Zeng et al., 2008). Where detailed historic binder information is missing, like the specification of binder source or perceived binder use, practical research alike this thesis can be conducted to determine the reasoning behind historic implementation.

Material mixtures

Because of the great variety of soils available for construction, discussing raw earth (thus also rammed earth) as a general material is nearly impossible (Norton, 1997). Examples of soil variations are their particle sizes, minerals present, and clay or silt contents. The mentioned variations, together with numerous other soil variations, all influence the working principles of rammed earth construction (Dethier, 2000). Research determining each possible binding principle in rammed earth mixtures is of the essence to optimise the use of local resources.

The binding principles of rammed earth mixtures can further be influenced by the use of additives, such as binders (as considered in this research) or fibres (Houben & Guillaud, 1994). Research into the influence of additives on the material mixture is essential. Practical experiments, like in this research, can show a first indication of potential material enhancement. Promising additives should be explored further to determine their influence on the binding principles of rammed earth construction. This would illustrate the way in which these additives can facilitate rammed earth material enhancements. Additional research is required into the effects of varying clay or loam types on the performance of binders in rammed earth mixtures, to be able to predict the impact of binders according to the available local materials.

Testing methods

To prove material enhancement as a result of additives in rammed earth material mixtures, extensive testing must be conducted. The formulation of a standardised set of testing for rammed earth samples, both with and without binders, is essential. This would allow all material developers to execute the same set of tests in a precise manner, thus producing results that can be universally compared. This would allow for the possibility of forming replicable conclusions regarding the material performance.

Building norms

To be able to successfully implement rammed earth into the current built environment, an effort should be made to form European building norms regarding the implementation of rammed earth: one for stabilised rammed earth and one for un-stabilised rammed earth (Fabbri & Morel, 2016). With said building norms in mind, rammed earth standardisation can be achieved. This would allow for cost and time effective rammed earth constructions (Rauch, 2020), making the material a valid alternative to common high-emission construction materials.

End-of-life

In 1791, François Cointeraux suggests using rammed earth construction remnant as fertiliser (Doat et al., 1991). Chapter *4.3.3. Moisture absorption test* suggests that rammed earth could potentially be re-used when combined with bio-based binders. Although material enhancements can be observed in all tests conducted in this research, the samples using bio-based binder do break down to their original material state during prolonged exposure to water. This is in contrast to the sample containing cement (an inorganic binder), which shows no sign of degradation during the moisture absorption test. This is in line with the statement of van Gorp (2018), that the use of cement in rammed earth prevents the material from being re-used. Research is to be conducted on the re-use of rammed earth samples containing bio-based binders. This would prove or disprove the hypothesis that the water solubility of bio-based binders allows for potential material re-use.

7. Reflection

7.1. Research reflection

Scope of research

The scope of the research is first of all created by limiting the location range. This is set to be Nortwestern Europe, representing a climate with heavy rainfall and periods of frost (Boudrea et al., 2023). The location also determines the required compressive strengths according to European building codes. The scope is further limited by the use of one type of a premixed rammed earth composition. Although the results are not guaranteed to work for all forms of rammed earth construction, the hypothesis is that the results will at least in part translate to alternative mixture compositions. The literature review discussing the historic information on rammed earth construction and binder use in raw earth architecture is limited, as it only provides the beginning of an overview of the available knowledge. Because the necessary information is hard to trace, completion of this overview is too complex for the scope of this research. Furthermore, binders that scored well in the matrix but were left (partially) undefined in literature, are removed for consideration. This significantly narrowed the group of potential binders, allowing for a sample group small enough to conduct relevant testing.

Research methods

To be able to test the produced samples against their material properties and weathering capabilities, a series of low-tech tests are conducted. These tests are illustrative in comparing the performance of each sample type. However, the results are not indicative of a comparison to traditional building materials like concrete or fired bricks. This means that only an improvement of the used rammed earth mixture can be concluded, which do not show their actual potential in contemporary Northwestern European construction.

Using machine executed testing, instead of the described tests based on human execution, would allow test results to be compared to industry standards of materials. This can include rammed earth standards as well as standards for alternative construction materials. Sample comparison is in part executed by personal observations. This again allows for a margin of human error. Application of well-defined criteria for damage assessment, and frequent gathering of quantitative data, can minimise this error.

Technological Readiness Level (TRL)

The Technological Readiness Level is a scale with which the maturity level of research for a technological advancement can be measured. There is a total of 9 levels, 9 being the highest. A project at level 9 has already produced successful conclusive results and is actively being implemented. This research into the bio-based binder suitable for rammed earth material enhancement is at TRL2: *Conceptual proof of principle or concept*. However, research at TRL1: *fundamental research*, is needed to gain an understanding of the principles responsible for the improvement of implemented binders (RON, 2023).

To further develop the TRL of the research, in-situ weathering testing can be done by constructing a 1:1 prototype. This would bring the research to TRL 3: *Experimental proof of principle or concept* (RON, 2023). After the principle is proven, more detailed research is required to formulate the optimal rammed earth mixture. This is a step back to TRL1. Ultimately, this research can be further developed into a potential prefabricated building panel, that can effectively be implemented in construction.

Scalability

For the proposed prototype at The Green Village* implementing the proposed binder (1.25% dehydrated albumen) a large amount of material is required: 77 kilograms of dehydrated chicken egg albumen. This translates to 308 kilograms liquid albumen, equalling 10.500 chicken eggs, or an average of just under 4000 eggs per cubic meter of the material. Naturally, this is completely unrealistic to scale-up to a full-sized home, let alone large-scale construction projects. To be able to implement the found results into construction, potentially a chemically derived equivalent to the albumen protein can be produced.

Additionally, acquiring the premade rammed earth mixture proved to be difficult. Within the Benelux there are only three producers of the material. The production of said 'product' is done on demand, but only after enough purchasers have shown interest. This results in long waiting times for acquiring rammed earth material. Moreover, the approached producers all suffered shortage of base material for the duration of this research, further delaying material delivery. The current rammed earth market of the Benelux is not ready for large scale use of the material. Similar situations are found in other Northwestern European regions, like Germany and France.

** Width: 2.7m, height: 2.53m, depth: 60cm or 30cm depending on wall height. Total volume of 2.7m^3.*

Implementation in built environment

As is, the findings of this research cannot be implemented in the built environment. The technology is not far enough in its development. For future implementation of the material, two choices can be made: in-situ construction versus prefabricated rammed earth blocks or panels (Minke, 2008). Both construction methods should make use of pneumatic rammers, resulting in a more uniform material performance.

Though historic rammed earth relied on in-situ material construction, the prefabricated blocks allow for material standardisation, both in dimensions and quality. Material standardisation makes way for the formation of building norms specified to rammed earth materials. This results in a material that can comply with the requirements of the built environment.

The sizing of prefabricated blocks can be determined to fit guidelines for maximum weight of manual handling; 25 kilograms (NEN, 2021). This produces rather small blocks, which can diminish the benefits of using rammed earth techniques. Potentially, alternative raw earth construction techniques would be more suitable for similar constructions. Alternatively, prefabricated panels could be made. These exceed weight limitations, thus must be transported and installed using machinery.

Rammed earth does allow for ample design choices regarding colour and tactility. Loam and clay are available in a wide array of shades and pigments can be added as desired. Furthermore, the surface of the material is pliable before its hardened state, allowing for the implementations of textures and patterns (Birznieks, 2013).

Construction sustainability

The rammed earth material, both with and without binders, is not yet ready for use on a large scale. However, the construction sustainability will be discussed with the assumption that the production of binders and rammed earth mixtures could sustainably be scaled-up.

Constructing buildings out of rammed earth hypothetically allows for re-use of the required building material at end-of-life (Minke, 2008). Re-use of materials leads to a lowered overall energy demand and lessened production of emissions during all stages of the construction process; production, packaging, shipping, and implementing of materials (Zuiderveen et al., 2023). When the material is not desired for re-use, it can be spread as fertiliser for soils (Doat et al., 2013), thus becoming zero-waste.

Societal sustainability

The societal benefits of the use of rammed earth construction starts with the promotion of a worldwide diversity of cultural identities (Dethier, 2020). The development of rammed earth as a construction material and method relies heavily on generations of local craftsmen, honing their skill through vernacular thinking, a cultural identity of place, and communal education (Minke, 2008). The tradition of earth building can thus symbolise the knowledge, know-how and way of living of its surrounding (Fissabre & Wilson, 2012). Furthermore, the local availability of the material supports local craft and trade, allowing people and materials to stay closer to home socially and practically (Dethier, 2020).

7.2. Personal reflection

Relationship to graduation orientation

The relationship between the graduation research of the implementation of bio-based binders in rammed earth construction and the graduation orientation of Building Technology is made by conducting research into the development of an alternative, sustainable, construction material. The role a student of Building Technology fulfils in the built environment is that of a middleman: neither being an architect, nor an engineer.

Being able to comprehend the ‘languages’ of both fields, Building Technology allows for material research to be conducted with a focus on the technical performance of samples, yet also paying mind to the experience of the senses in relation to the samples. The behaviour of the material, colour – smell – tactility – sound, is perceived and noted during each step of the research, alongside their technical prestation. This provides not only the intended practical test results, useful for engineers, but also an overview of the unintended test results relating to the human senses, useful for architects.

The received education on design choices and design processes allowed for me to have an open mind while experimenting with the material. Applying design through explorations, as practiced in the Bachelors in Delft, was suitable for the initial material observations. Approaching the addition of binders to the existing rammed earth mixture as ‘explorations’ allowed for more unbiased material findings. My focus in this testing phase was not to achieve the research aim, but rather to observe the altered material behaviour as a result of implementation of binders. These observations, however, did help in ultimately answering the research questions. This is not unlike making quick and simple form explorations in an architectural design, where the aim is to discover more about the design problematics, rather than solving them.

Additionally, the necessary change of the built environment from inorganic to alternative (bio-based) materials is undeniable. For climate goals to be reached, a ‘material revolution’ is required. All these alternative materials are at such an experimental level of development that hands-on research, like this thesis, is required to gain full material understanding.

Graduation process

Undergoing the process of this thesis graduation allowed me to grow immensely as a researcher as well as a designer. The main cause I would attribute to this growth is the amount of hands-on research the topic allowed me to conduct.

In this research I combined in depth theoretical background of a material, with a lack of preconceived practical notions of possible material behaviours, having never practically used raw earth materials beforehand. This resulted in a child-like, though systematic, approach to the initial material experimentation phase, allowing me to discover the material behaviours through sensory observation.

An intangible understanding of the material was gained with the use of sensory observations, which the literature did not provide me with. Although several authors provide descriptions of similar sensory experiences in using raw earth materials, experiencing it for myself allowed retroactively for a much deeper understanding of the considered literature. The active involvement with the material gave me the ability to predict the potential functionality of the material before testing confirmed these results, thus more efficiently finding solutions to problems that presented themselves.

The opportunity to practically experience a material adds a level of innate material understanding that cannot be learned from books or through theoretical teaching. My usual design approach is that of form follows function. This tends to trap my design process in ridged thinking patterns, designing with logic over instinct. Although this research was set out to be the similar approach of 'material follows function', the active involvement with the material forced me into intuitive research, based on feeling and experiencing. This allowed me to forego some of my usual rigidity and be truly able to let the material speak to me.

Several tutors tried conveying this same experience throughout the TU Delft education I received, highlighting the importance of design through explorations, yet their attempts only resulted in a theoretical understanding of this concept. Only through this research process was I able to connect this theoretical concept with experiences, finding the true benefits of this approach.

I would like to propose more involvement with materials in the educational program of the TU Delft. The predicted 'material revolution', necessary for meeting climatic goals, requires researchers that have a true understanding of material functioning. As I experienced myself, this cannot be reached through theory alone. Knowing how materials behave, what their strengths and weaknesses are, and where and how they can be altered gives future designers and engineers more freedom for alternative thinking in their work.

Gaining practical experience with more than one material, could enhance this effect even further. I expect a general knowledge base of practical material behaviours to allow students the be able to know on an instinctive level which materials are suitable for their desired design outcome. When a chosen material does not fit the design needs, they would be more capable of finding a suitable alternative based on the desired material behaviours.

References

- Abari. (2015). *Adobe, cob and bamboo*. https://abari.earth/oldprojects/2015/12/3/adobe-cob-and-bamboo
- Auroville Earth Institute. (n.d.). *Technique Overview*. https://www.earth-auroville.com/world_techniques_introduction_en.php
- Babu, T. N., & Neeraja, D. (2017). A experimental study of natural admixture effect on conventional concrete and high volume class F flyash blended concrete. *Case Studies in Construction Materials*, *6*, 43–62. https://doi.org/10.1016/j.cscm.2016.09.003
- Backsteinbau. (2020). *Lehmbau und Lehmsteine.* https://backstein-bau.de/lehmbau-und-lehmsteine/
- Basanna, N. H., Shivaprakash, S. H., Bhimahalli, A., Parameshwarappa, P. K., Gaudin, J. (2020). Role of stabilizers and gradation of soil in rammed earth construction. *Journal of Materials in Civil Engineering*, *32*(5). https://doi.org/10.1061/(asce)mt.1943-5533.0003112
- Beat Buhler. (n.d.). Rammed earth – the building material of the future. https://changelab.exchange/portfolio/rammed-earth-the-building-material-of-the-future/
- Birznieks, L. (2013). *Designing and building with compressed earth*. TU Delft.
- Boudreau, D., McDaniel, M., Sprout, E., Turgeon, A. (October, 2023). *Europe: Resources.* https://education.nationalgeographic.org/resource/europe-resources/
- Bremmer, M. (2020). *3D Printing with Bio-Based Materials: Designing a toolkit to guide makers into sustainable material development*. TU Delft.
- Canivell, J., Martín-Del-Río, J. J., Ganfornina, R. M. F., & Rubio-Bellido, C. (2020). Rammed Earth Construction: A proposal for a statistical quality control in the execution process. *Sustainability*, *12*(7), 2830. https://doi.org/10.3390/su12072830
- Climate ADAPT. (n.d.). North West Europe. Climate ADAPT. https://climate-adapt.eea.europa.eu/en/countries-regions/transnational-regions/north-west-europe
- Cockram, M. (February, 2018). *Continuing Education Center - Rammed Earth.* https://continuingeducation.bnpmedia.com/courses/multi-aia/rammed-earth/2/
- Correia, M., Dipasquale, L., Mecca, S., Mileto, C. (2011). *TERRA EUROPAE: Earthen Architecture in the European Union*. ETS.
- CRAterre. (1994). *La roue des techniques.* https://craterre.hypotheses.org/3917
- CRAterre. (n.d.). *CRATerre Home*. http://craterre.org
- D'A Architektur. (n.d.). *Warum Lehm?* https://daarchitektur.com/leistungen/fachplanung-lehmbau
- Dethier, J. (2020). *The Art of Earth architecture: Past, Present, Future*. Thames & Hudson Ltd.
- Correia, M., Dipasquale, L., Mecca, S., Mileto, C. (2011). TERRA EUROPAE Earthen Architecture in the European Union. ETS, PISA.
- Doat, P., Hays, A., Houben, H., Matuk, S., Vitoux, F. (1991). *Building with earth*. CRATerre.
- Dutch Egg Powder Solutions B.V. (n.d.). *How is egg white powder made.* Wulro. https://www.deps.eu/how-is-egg-white-powder-made/
- Eyeson, J. (2022). What is rammed earth construction & how to build a wall step by step? https://www.hiveearth.com/post/what-s-coming-up#viewer-bhfrt
- Eyeson, J. (2022, December 31). What is rammed earth construction & how to build a wall step by step? *Hive Earth*. https://www.hiveearth.com/post/what-s-coming-up#viewer-6aqfu
- Fabbri, A., Morel, J.C. (2016). *Earthen materials and constructions.* Elsevier.
- Federico Cairoli. (2021). *La Casa Intermedia.* https://equipodearquitectura.com/proyectos/la-casa-intermedia/

- Fehrgroup. (n.d.). *Poured earth concrete: Virtuous construction.* https://fehrgroup.com/en/precast-wall/poured-earth-concrete/
- First in Architecture. (n.d.). Rammed Earth Construction. https://www.firstinarchitecture.co.uk/rammed-earth-construction/
- Fissabre, A., Wilson, A. (2012). *Lehmbaupropaganda: contrasting ideologies of sustainability in earth building literature*. RWTH.
- Ganotopoulou, E. (2014). *Biodegradable materials. A research & design handbook; enhancing the use of biodegradable materials on building's envelopes in the Netherlands.* TU Delft.
- GOLEHM. (2020). *Bautechniken Massivlehm in Mitteldeutschland: Der Stampflehmbau.* https://www.golehm.de/massivlehmbau/bautechniken-massivlehm
- GOLEHM. (2020). *Bautechniken Massivlehm in Mitteldeutschland: Der Lehmsteinbau.* https://www.golehm.de/massivlehmbau/bautechniken-massivlehm
- GOLEHM. (2021). *Bautechniken Massivlehm in Mitteldeutschland: Lehm-Stroh-Gemisches*. https://www.golehm.de/massivlehmbau/bautechniken-massivlehm
- GOLEHM. (n.d.). *Bautechniken Massivlehm in Mitteldeutschland.* https://www.golehm.de/massivlehmbau/bautechniken-massivlehm
- Gramlich, A. N. (2013). *A concise history of the use of the rammed earth building technique including information on methods of preservation, repair, and maintenance*. University of Oregon.
- Grunacker, M. (2021). *Building Design for Sustainability Master's Thesis*. Chalmers School of Architecture.
- Gunnarsdóttir, S. (2021). *Earth and Vernacularity: Reviving vernacular architecture in Iceland with rammed earth construction.* TU Delft.
- Gustavsson, L., Sathre, R. (2006). *Effects of energy and carbon taxes on building material competitiveness.* Ecotechnology, Mid Sweden University.
- Houben, H. and Guillaud, H. (1994) *Earth construction; a comprehensive guide.* Practical action publishing, pp. 5-8, 72, 78, 202-207
- Human, T. (2017). *Why use 'Deadmen' in Cob walls.* https://moreecological.wordpress.com/2017/08/18/why-use-deadmen-in-cob-walls/
- Jaquin, P., Augarde, C. E., Gerrard, C. (2008). Chronological description of the spatial development of rammed earth techniques. *International Journal of Architectural Heritage*, *2*(4), 377–400. https://doi.org/10.1080/15583050801958826
- Jaquin, P., Augarde, C. E. (2012). *Earth Building: History, Science and Conservation*. IHS BRE Press.
- Joffroy, T., Zawistowski, K., Zawistowski, M. (2020). 'Evolving Vernacular: Reinventing Rammed Earth in the Context of Twenty-First Century Seismic Regulation.' *Technology|Architecture + Design*, 4:2, 158-165, DOI: 10.1080/24751448.2020.1804758
- Keefe, L. (2005). *Earth Building: Methods and materials, repair, and Conservation*. Routledge.
- KNMI. (n.d.). *Uitleg over extreme neerslag: Veelgestelde vragen over extreme neerslag in Nederland*. https://www.knmi.nl/kennis-en-datacentrum/uitleg/extreme-neerslag
- Langejans, G. H. J., Aleo, A., Fajardo, S., & Kozowyk, P. R. B. (2022). Archaeological Adhesives. *Oxford Research Encyclopedia of Anthropology* (pp. 1-54). https://doi.org/10.1093/acrefore/9780190854584.013.198
- Lubelli, B. (2018). Clay-Based Building Materials in Traditional Kyomachiya. In van Thoor, M. & Stroux, S. (Eds.), *Heritage, History and Design Between East and West: A Close-Up on Kyoto's Urban Fabric* (pp. 55-63). TU Delft.
- Maniatidis, V., Walker, P. (2003). *A Review of Rammed Earth Construction.* Bath University.
- Manning, C. (2023). *Technological readiness levels*. NASA. https://www.nasa.gov/directorates/somd/space-communications-navigation-program/technology-

readiness-levels/#:~:text=Technology%20Readiness%20Levels%20(TRL)%20are,based%20on%20the%20projects%20progress.

- Maravelaki-Kalaitzaki, P., Kapetanaki, K., Papayianni, I., Ioannou, I., Faria, P., Álvarez, J. L., Stefanidou, M., Nunes, C., Theodoridou, M., Ferrara, L., & Toniolo, L. (2023). RILEM TC 277-LHS report: additives and admixtures for modern lime-based mortars. *Materials and Structures*, *56*(5). https://doi.org/10.1617/s11527-023-02175-z
- Marsh, A., Kulshreshtha, Y. (2021). *The state of earthen housing worldwide: how development affects attitudes and adoption.* Building Research & Information.
- McDowell, E., Weller, C. (2020). *Inside Coober Pedy, the Australian mining town where residents live, shop, and worship underground.* https://www.businessinsider.com/inside-coober-pedy-australias-underground-town-2016-1?international=true&r=US&IR=T#with-the-homes-cave-like-exteriors-the-process-of-going-underground-may-seem-like-a-venture-into-the-unknown-7
- Minke, G. (2000). *Earth construction handbook: the building material earth in modern architecture.* WIT Press.
- Minke, G. (2006). *Building with Earth: Design and Technology of a Sustainable Architecture*. Birkhäuser.
- NEN. (2015). ASTM C293/C293M - 15 en. NEN. https://www.nen.nl/astm-c293-c293m-15-en-1093500
- NEN. (2019). *NEN-EN 12390-3:2019 en.* NEN. https://www.nen.nl/nen-en-12390-3-2019-en-260976
- NEN. (2021). *NEN-ISO 11228-1:2021 en*. NEN. https://www.nen.nl/en/nen-iso-11228-1-2021-en-288414
- Ni, H., Xiong, Z., Li, Y., Li, L., Liu, F., Su, D., Zhou, Y., Zhang, Z., & Lu, J. (2021). Feasibility of a novel prefabricated concrete wall system for masonry structures. *Structures*, *32*, 1907–1920. https://doi.org/10.1016/j.istruc.2021.04.005
- Norton, J. (1997). *Building with Earth. A handbook.* Second edition. London, Intermediate Technology Publications Limited.
- Picryl. (2016). *Earth Lodge in 2015 (Mississippian Council Chamber).* https://picryl.com/media/earth-lodge-in-2015-mississippian-council-chamber-6bcd8c
- Rael, R. (2009). *Earth Architecture*. Princeton Architectural Press.
- Rampazzi, L., Colombini, M. P., Conti, C., Corti, C., Lluveras-Tenorio, A., Sansonetti, A., & Zanaboni, M. (2016). Technology of Medieval Mortars: An Investigation into the Use of Organic Additives. *Archaeometry*, *58*(1), 115–130. https://doi.org/10.1111/arcm.12155
- Rath, R. (2004). Earthen building in the former Soviet occupied zone and the former GDR: 1945−1989. TU Berlin.
- Rauch, M. (2020). *Unstabilized rammed earth – 100% EARTH. Why is it so difficult to trust 100%?* https://www.dachverband-lehm.de/lehm2020_online/
- Reddy, B. V. V., & Jagadish, K. S. (2003). Embodied energy of common and alternative building materials and technologies. *Energy and Buildings*, *35*(2), 129–137. https://doi.org/10.1016/s0378-7788(01)00141-4
- RSPCA. (2021). *What happens with male chicks in the egg industry*. https://kb.rspca.org.au/knowledge-base/what-happens-with-male-chicks-in-the-egg-industry/
- Rijksdienst voor Ondernemend Nederland. (2023). *Technology Readiness Levels (TRL).* Ministerie van Economische Zaken en Klimaat. https://www.rvo.nl/onderwerpen/trl
- Rijksdienst voor Ondernemend Nederland. (2024). *Interreg North-West Europe (NWE)*. Ministerie van Infrastructuur en Waterstaat. https://www.rvo.nl/subsidies-financiering/interreg/interreg-nwe#voor-wie%3F

- Sankhla, S., Chaturvedi, A., Aparna, K., Mulinti, S. (2011). Studies on Effect of Packaging Material and Irradiation on Storage Stability of Jaggery. *Sugar Tech*. 13. 229-235. 10.1007/s12355-011-0090-4.
- Sgouropoulou, E. (2013). *Possibilities of applying biodegradable materials in solid building envelopes in the Netherlands*. TU Delft.
- Spiegel, R., Meadows, D. (1999). *Green Building Materials: A Guide to Product Selection and Specification*. John Wiley & Sons, Inc.
- Stanfield, D. (October, 2022). *Turf house Iceland.* https://www.pexels.com/photo/turf-house-19511045/
- Stanfield, D. (September, 2022). *Moss Covered Viking Building in Skalholt Historical Site of Iceland*. https://www.pexels.com/photo/moss-covered-viking-building-in-skalholt-historical-site-of-iceland-19267214/
- Taghiloha, L. (2013). *Using rammed earth mixed with recycled aggregate as a construction material*. UPC Barcelonatech. https://core.ac.uk/reader/41817160
- Terra Incognita. (2011). *2011 Map of Earthen Heritage in the European Union*. Edizioni ETS.
- Uberprutser. (2014). *Openluchtmuseum Ellert en Bammert te Schoonoord – Plaggenhut.* https://commons.wikimedia.org/wiki/File:Openluchtmuseum_Ellert_en_Bammert_te_Schoonoord_-_Plaggenhut.jpg
- UKU. (n.d.). *CEB - compressed earth block.* https://uku.eu/en/clay-products/ceb-compressed-earth-block/
- Uni Terra. (n.d.). *Associations*. https://www.uni-terra.org/associations#europe
- United Nations Environment Programme, Yale Center for Ecosystems + Architecture. (2023). *Building Materials and the Climate: Constructing a New Future*. https://wedocs.unep.org/20.500.11822/43293
- Van Gorp, M. *Experimental Study of the in-plane behaviour of rammed earth, strengthened with TRM.* (2018) KU Leuven.
- Walker, P., Keable, R., Martin, J., Maniatidis, V. (2010). *Rammed earth: design and construction guidelines*. BRE Bookshop.
- Wikipedia. (n.d.). *Earthship*. https://en.wikipedia.org/wiki/Earthship
- Zawistowski, K., Zawistowski, M., Joffroy, T. (2020). *Evolving Vernacular: Reinventing Rammed Earth in the Context of Twenty-First Century Seismic Regulation*. Technology|Architecture + Design, 4:2, 158-165, DOI: 10.1080/24751448.2020.1804758
- Zeng, Y., Zhang, B., & Liang, X. (2008). A case study and mechanism investigation of typical mortars used on ancient architecture in China. *Thermochimica Acta*, *473*(1–2), 1–6. https://doi.org/10.1016/j.tca.2008.03.019
- Zuiderveen, E. A., Kuipers, K., Caldeira, C., Hanssen, S. V., Van Der Hulst, M. K., De Jonge, M. M., Vlysidis, A., Van Zelm, R., Sala, S., Huijbregts, M. a. J. (2023). The potential of emerging bio-based products to reduce environmental impacts. *Nature Communications*, *14* (1). https://doi.org/10.1038/s41467-023-43797-9

Appendix 1. Description earthen construction techniques

1. DIG

Type: **Dug out**
Location: China, Tunisia, Australia.
Definition: “Dwelling dug directly out of a layer of the earth’s crust.” (Houben & Guillaud, 1994, p.164)

A shelter is dug directly into the earth, most often found in areas that have a hot and dry climate with soft soil, tuff, loess, or porous lava. The shelter can be dug both horizontally, creating caves into a hillside, or vertically, into the ground of plains (Auroville Earth Institute, n.d.).

Example Dug out:

Fig. 3

Tunisia, Matmata. (Auroville Earth Institute, n.d.)

Fig. 4

Australia, Coober Pedy. (Business Insider, 2020)

2. COVER

Type: **Earth Covering – Earth-sheltered space**
Location: Netherlands, Scandinavia, worldwide, focus on extreme cold and extreme hot climates.
Definition: "A structure built in one or other material, but not earth, is encased and covered with soil." (Houben & Guillaud, 1994, p.164)

Northwestern European heritage

In Iceland and Norway sod is observed to be used to preserve and cover roofs of traditional wood houses throughout time (Houben & Guillaud, 1994). In Scandinavian countries in general, this same architecture can be found. Birch bark was peeled in thin strips and applied in a number of layers to provide waterproofing (Auroville Earth Institute, n.d.).

Earth covering; None-earthen structures with earth covered roofs, found all over the world. In Scandinavia, the earth used to cover the roofs contains roots for improved cohesion and thermal mass. Underneath the earth, birch bark was applied for waterproofing. Green roofs can be considered modern earth coverings (Auroville Earth Institute, n.d.).

Example Earth Covering: **Fig. 5**

Netherlands, Schoonoord. (Uberprutser, 2014)

Fig. 6

Iceland, Skalholt. (Stanfield, September 2022)

Earth-sheltered space; None-earthen construction completely covered in earth, found all over the world. The covering of earth provides thermal mass for both hot and cold climates (Auroville Earth Institute, n.d.).

Example Earth-sheltered space: **Fig. 7**

Finland, Helsinki. (Jonathan, 2015)

Fig. 8

United States, Ocmulgee. (Picryl, 2016)

3. FILL

Type: **Earth filling**
Location: Modern, worldwide with focus on Germany and the USA.
Definition: "Ungraded soil is used to fill hollow materials used as a framework." (Houben & Guillaud, 1994, p.164)

A container gets filled with humid soil, fulfilling the function of a framework. The container can either be removed after hardening of the earth or can be kept in place. The earth provides thermal mass and acoustic insulation to otherwise light construction. Traditional examples implement wooden lattice works, modern examples involve synthetic textiles held in place by wooden posts and barbed wire. These modern examples can be called Superadobe, Eco-domes, or sandbag architecture (Auroville Earth Institute, n.d.)

Example Earth filling:

Fig. 9

Germany, Kassel - (Auroville Earth Institute, n.d.)

Fig. 10

USA, California - (Auroville Earth Institute, n.d.)

4. CUT

Type: **Sod – Cut Blocks**
Location: Sod: England, Scandinavia, USA, South America. Cut Blocks: Africa, India.
Definition: "Blocks of earth are cut directly from the ground." (Houben & Guillaud, 1994, p.164)

Northwestern European heritage

Sod architecture, both from grass sods and peat sods, can be found throughout Scandinavia on stone and wood structures (Auroville Earth Institute, n.d.). Especially Iceland has a well-documented history of this archetype, using peat sods. Turf, or dried peat, was readily available and insulated buildings well against the cold climate. Farmsteads were purposefully located near peatlands to provide building materials. These farms required constant upkeep, due to the changes in the living turf over time, adjusting frequently to the seasons. This same turf as applied on the roof was used to fill in gaps between the stones of walls, up to 2 meters in thickness (Gunnarsdóttir, 2021).

Sod; Grass sod consists of stacked blocks cut from earth with fresh grass roots still in place (Auroville Earth Institute, n.d.). Peat sod, called turf once dried, consists of partially decayed plant-matter and is found in soils called histosol. The turf is cut into blocks and stacked. Often, peat was used as a fuel instead of construction material (Ganotopoulou, 2014). The consistency of both blocks provides stability and thermal mass.

Example Sod: **Fig. 11**

Uruguay, Montevideo - (Auroville Earth Institute, n.d.)

(Left grass, right peat) **Fig. 12**

Iceland, unknown. (Stanfield, October 2022)

Cut blocks; Soil containing concretions of carbonates, providing cohesion to the material, is cut in blocks, and stacked like bricks. Lateritic soils in tropical climates provide either soft soil (plinthite), setting when in contact with air, or hard crusts (petroplinthite) which are previously dried plinthite (Auroville Earth Institute, n.d.).

Example Cut Blocks: **Fig. 13**

India, Orissa - (Auroville Earth Institute, n.d.)

Fig. 14

Burkina Faso, Kari Kari - (Auroville Earth Institute, n.d.)

5. COMPACT

Type: **Compressed Blocks – Tamped Blocks – Rammed Earth**
Location: CB: France, worldwide. TP: Germany, worldwide. RE: France, Spain, Italy, worldwide.
Definition: "Blocks or massive walls are formed by compressing soil in moulds or formwork." (Houben & Guillaud, 1994, p.164)

Northwestern European heritage

Although scarce, examples of historic moulded earth blocks can be found in Germany. Because the knowledge on the topic is limited, compressed blocks and tamped blocks will be considered the same for their German history. Most commonly, these blocks are observed stacked in gables, as techniques like cob are hard to implement structurally in these sharp corners. The blocks were held together using clay mortar. More often than not, organic additives were added to the clay mixture of these blocks. Known additives are straw and broken roof tiles (GOLEHM, n.d.).

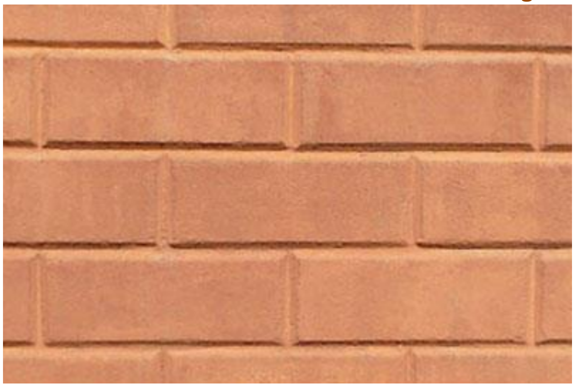
Compressed blocks; Also known as CEB, contains a mixture of soil, clay, water, and possibly stabilisers. This mixture gets compressed in moulds, using a press, and is then left to air dry. The resulting blocks can be utilised like bricks (Ganotopoulou, 2014). Compression provides stronger and denser qualities compared to non-compressed earth blocks, allowing for higher and thinner walls. Modern compressed blocks almost always contain cement, being called Compressed Stabilised Earth Blocks, or CSEB (Auroville Earth Institute, n.d.).

Example Compressed Blocks:

Fig. 15

England, unknown. (UKU, n.d.)

Fig. 16



India, Auroville - (Auroville Earth Institute, n.d.)

Tamped blocks; A mixture of soil, clay, water, and possibly stabilisers. This mixture gets compressed in moulds, using a rammer, and is then left to air dry. The resulting blocks can be utilised like bricks (Ganotopoulou, 2014). Compression provides stronger and denser qualities compared to non-compressed earth blocks, allowing for higher and thinner walls (Auroville Earth Institute, n.d.).

Example Tamped Blocks:

Fig. 17

Germany, Mücheln am Geiseltalsee. (GOLEHM, 2020)

Fig. 18

Germany, Brehna. (GOLEHM, 2021)

Rammed earth; Also known as Pisé de terre, contains a mixture of soil, clay, water, gravel, and possibly stabilisers. Layers of this mixture get compressed in a mould, using a rammer, to 50% of their hight. The compression can be done either manually or mechanically. Layers get added on top of each other until desired hight is reached (Ganotopoulou, 2014). The compression provides improved compressive strength and water resistance (Auroville Earth Institute, n.d.).

Example Rammed Earth:

Fig. 19

France, Albon. (Auroville Earth Institute, n.d.)

Fig. 20

Germany, Glebitzsch. (GOLEHM, 2020)

6. SHAPE

Type: **Shaped Earth**
Location: Africa.
Definition: "Thin walls are built by direct manual shaping of plastic soil." (Houben & Guillaud, 1994, p.164)

Plastic earth shaped into rolls, similar to the technique of making pots, layered vertically on top of each other, and smoothed out. Braids or twists of natural fibres can be soaked in clay and used as the mixture (Dethier, 2020). Soils are often enhanced using natural additives as binders, although detailed knowledge is lost to time. Requires minimal and simplistic tools and allows for free form shaping. Requires extensive knowledge on both soil quality/mixtures and construction principles (Auroville Earth Institute, n.d.).

Example Shaped Earth:

Fig. 21

Niger, unkown. (Auroville Earth Institute, n.d.)

Fig. 22

Cameron, Mousgoum. (Auroville Earth Institute, n.d.)

7. STACK

Type: **Cob**
Location: France, England, Germany, Africa, Asia, modern focus on USA.
Definition: "Thick walls are built up by piling up balls of earth on top of each one another." (Houben Guillaud, 1994, p.164)

Northwestern European heritage

Cob is considered to have originated from indigenous European cultures. It is, for example, known that the Gauls, a group of Celtic people living mostly in France and Germany, used cob as a technique for constructing their dwellings during the Iron Age. Their homes are often described in archaeology as rudimentary, of which nothing remains but holes in the ground. This can however not be proven or disproven (Dethier, 2020). In Central Germany, building with cob can be traced back in sources to the 16th century. Both dwellings and farmsteads were constructed using the 'Weller method' and plastered after drying. The walls are documented to have been 0.60-1.00 meters. Public buildings were often not plastered (GOLEHM, n.d.).

Cob: Known as cob in England, also known as bauge in France. Plastic soil formed by hand in balls (Auroville Earth Institute, n.d.), stacked 40 to 60cm high while moist, then adjusted and smoothed (Dethier, 2020). Each layer must be dried before applying the next (Ganotopoulou, 2014). Straw, grasses, or thin twigs can be added to the mixture to provide added stability (Dethier, 2020).

Example cob: **Fig. 23**

France, Normandie. (Auroville Earth Institute, n.d.)

Fig. 24

France, unknown. (Auroville Earth Institute, n.d.)

8. MOULD

Type: **Hand Shaped Adobe – Hand Moulded Adobe – Machine Moulded Adobe**
Location: HSA: Germany, worldwide. HMA: Spain, Germany, worldwide. MMA: Modern, worldwide.
Definition: "Earth is moulded either by hand or in moulds of various shapes." (Houben & Guillaud, 1994, p.164)

Northwestern European heritage

As precise information on adobe in Europe is hard to find, hand shaped adobe and hand moulded adobe will be considered the same for their history. Adobe was gradually brought over to Europe from the (East Asia Minor, Anatolia, the Balkans, and Greek trading posts) starting at the 5th century BCE (Dethier,2020). Roman architect Vitruvius mentions adobe in his 'Ten Books of Architecture", written between 30-20 BC, as being used for homes, public buildings, city walls, and palaces (Birznieks, 2013). Eventually, adobe products shaped the way for the industrialisation of the construction sector (Dethier, 2020).

Hand shaped adobe; contains a mixture of soil, clay, water, oftentimes fibres, and possibly stabilisers (Dethier, 2020). Shaped into balls or elongated loaves by hand and left to dry in the sun (Auroville Earth Institute, n.d.).

Example Hand Shaped Adobe: **Fig. 25**

Saudi Arabia, Al Diriyah. (Auroville Earth Institute, n.d.)

Fig. 26

India, Chitradurga. (Auroville Earth Institute, n.d.)

Hand moulded adobe; contains a mixture of soil, clay, water, oftentimes fibres, and possibly stabilisers (Dethier, 2020). Shaped into bricks using parallelepiped wooden moulds and left to dry in the sun (Auroville Earth Institute, n.d.).

Example Hand Moulded Adobe: **Fig. 27**

Spain, Bardallur. (Auroville Earth Institute, n.d.)

Fig. 28

Germany, unknown. (D'A Architektur, n.d.)

9. EXTRUDE

Type: **Extruded Earth**
Location: Modern, worldwide.
Definition: "A soil paste is extruded by a powerful machine and building elements are then made from the extruded material." (Houben & Guillaud, 1994, p.164)

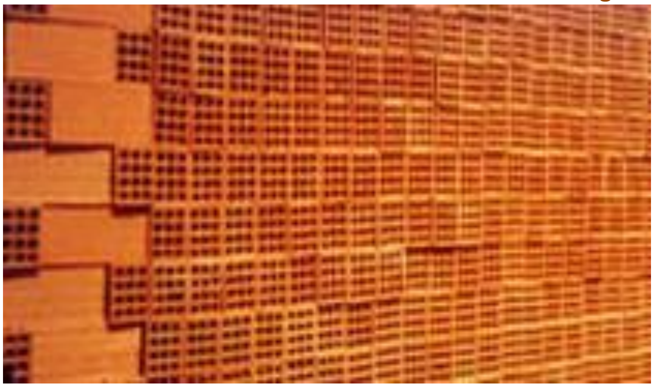
Stabilised earth in plastic state, mechanically extruded through mould into desired shape. Resulting shape is cut into slices, forming oftentimes hollow blocks. Modern technique, comparable to that of fired brick. Soil required for extruded earth must be much sandier than that used for bricks, causing for a more abrasive mixture, damaging machinery (Auroville Earth Institute, n.d.).

Example:

Fig. 31

France, unkown. (Auroville Earth Institute, n.d.)

Fig. 32



USA, New Mexico. (Auroville Earth Institute, n.d.)

10. POUR

Type: **Poured Earth**
Location: Modern, worldwide.
Definition: "Liquid soil poured into formwork or moulds serves as a kind of concrete." (Houben & Guillaud, 1994, p.164)

Soil in liquid state, poured layer by layer into formworks or multipiece moulds. Consistency of soil must be sandy or gravely, must be stabilised (Dethier, 2020). High water content makes poured earth susceptible to shrinkage & cracking (Auroville Earth Institute, n.d.).

Example:

Fig. 33

France, Reichshoffen. (Fehrgroup, n.d.)

Fig. 34

France, Reichshoffen. (Fehrgroup, n.d.)

11. FORM

Type: **Straw-clay – Cob on Post**
Location: Straw-clay: Germany, Europe. Cob on Post: England, Europe.
Definition: "A slurry consisting of clayey soil binds shreds of straw fibre to produce a fibrous material." (Houben & Guillaud, 1994, p.164)

Northwestern European heritage
For the preparation of straw-clay, various straws were originally used; wheat, barley, rye, winter barley, hay, and heater can be observed. This straw-clay mixture was originally used to fill-in wooden structural frames but was later adapted into pre-made blocks. The use of straw-clay doesn't ask for specialised tools or knowledge, so the method was commonly used on simple housing, constructed by its residents (Houben & Guillaud, 1994).

Straw-clay; Also known as light-earth. Liquid clay poured on straw, cut to required length, then mixed. Lightweight, providing much thermal insulation, but little load-bearing capacity. Must be encompassed into structural wooden frame. Can alternatively be made into prefab blocks (Auroville Earth Institute, n.d.). Previously, this technique was known as half-timbering (Dethier, 2020).

Example Stray-clay:

Fig. 35

Belgium, Overisse. (Auroville Earth Institute, n.d.)

Fig. 36

Germany, Ostrau. (GOLEHM, 2021)

Cob on post; Liquid clay poured on straw, cut to required length, then mixed. Lightweight, providing much thermal insulation, but no bearing capacity. Must be worked around wooden posts (Houben & Guillaud, 1994).

Example Cob on Post:

Fig. 37

Portugal, unkown. (Human, 2017)

Fig. 38

Nepal, Kathmandu. (Abari, 2015)

12. APPLY

Type: **Wattle and Daub**

Location: Netherlands, France, Europe, Asia.

Definition: "Clayey soil mixed with fibres is applied in a thin layer to fill in a support." (Houben & Guillaud, 1994, p.164)

Northwestern European heritage

In the 7th millennium BCE, better known as the Stone Age, new technology of forming earth settlements come over from Turkey to Eastern Europe. An early example of this is the Danubian house, being made up to 45m in length. Due to the wide-spread forest in the Danube Valley, homes were built using thick wooden posts anchored in the ground, filled in with wattle and daub. During the span of about two thousand years, wattle and daub slowly spread westwards across Europe. Local alterations to the method were made, to provide for local materials and conditions, however the archetype of a loadbearing wooden framework filled in with earth could be found in Europe for centuries afterwards. Even now the technique still shows itself in numerous rural and urban homes (Dethier, 2020).

As well as cob, wattle and daub is described to be used by the Gauls for constructing their homes, see *7. Cob*. An example of this construction technique is the Verberie House in the Oise region of France, constructed in the Second Iron Age (3rd-1st century BCE), had an enormous floorplan of 250 square metres. The walls were made of a wooden structure tightly packed with an earthen mixture, and were covered with a thatched saddle roof, sheltering them from heavy rainfall (Dethier, 2020).

Wattle and daub: Malleable earth mixed with fibres and potentially animal dung, used on both sides to fills the gaps of a load-bearing framework (Dethier, 2020). This load-bearing framework, wattle, consists of a weft using stiff organic material (Ganotopoulou, 2014). These materials include reeds, sticks, or bamboo. In France the earth mixture was stabilised using horse urine, providing water resistant properties (Auroville Earth Institute, n.d.).

Example Wattle and Daub:

Fig. 39

France, Alsace. (Auroville Earth Institute, n.d.)

Fig. 40

France, Saint Triviers de Court. (Auroville Earth Institute, n.d.)

Appendix 2. Criteria matrix

1. Name	2. Catego	3. His/Mc	4. Type of	5. Locatio	6. Source	7. Bio-bas	8. Low co	9. Availab	10. Local	11. Sus. A	12. Sus. P	13. Recyc	16. Comp	15. Accep	14. Waste	17. Plasti	18. Water	19. Freez	20. Score
Fish oil	1	His.												-1	0	0	1	0	0
Fat	1	His.												-1	1	0	1	0	1
Blood	1	His.												-1	1	0	1	0	1
Glue	1	His.												-1	1	0	0	0	0
Fish glue	1	His.												-1	1	0	0	0	0
Hair/fur	1	His.												-1	1	0	0	0	0
Animal urine	2	His.												-1	1	0	1	1	2
Shells	2	His.												1	1	0	1	1	4
Egg, white	2	His.												1	0	1	1	0	3
Egg, yolk	2	His.												1	0	1	1	0	3
Dung, cow	2	His.												0	1	1	-1	0	1
Dung, camel	2	His.												0	1	1	-1	0	1
Dung, horse	2	His.												0	1	1	-1	0	1
Casein	2	His.												1	-1	0	1	0	1
Milk products	2	His.												1	-1	0	1	0	1
Beeswax	2	His.												1	-1	1	1	0	2
Jaggery	3	His.												1	-1	1	1	1	3
Molasses	3	His.												1	-1	1	1	1	3
Sugar, refined	3	His.												1	-1	1	1	1	3
Kapok seed flour	3	His.												1	-1	1	0	0	1
Rye dough	3	His.												1	-1	0	0	0	0
Starch	3	His.												1	-1	1	1	1	3
Glutenous rice	3	His.												1	-1	1	1	1	3
Soy	3	His.												1	-1	1	1	1	3
Seaweed	3	His.												1	0	1	0	0	2
Beer	3	His.												1	-1	1	0	0	1
Vegetable juice	3	His.												0	0	0	0	0	0
Keratin, plant	3	His.												1	0	0	1	1	3
Tannin	3	His.												1	1	0	1	0	3
Latex	3	His.												1	-1	1	1	1	3
Plant mucilage	3	His.												1	1	1	1	1	5
Cacti	3	His.												1	-1	1	1	1	3
Agar	3	His.												1	0	1	0	0	2
Hardwood	4	His.												1	-1	0	1	0	1
Coconut shell	4	His.												1	1	0	1	0	3
Vegetable	4	His.												1	1	0	1	0	3
Bone	4	His.												-1	1	0	1	0	1
Coconut	5	His.												1	-1	0	1	1	2
Cottonseed	5	His.												1	-1	0	1	1	2
Linseed	5	His.												1	-1	0	1	1	2
Castor	5	His.												1	-1	0	1	1	2
Saponified palm	5	His.												-1	-1	0	1	1	0
Shea	5	His.												1	-1	0	1	1	2
Olive	5	His.												1	-1	0	1	1	2
Sesame	5	His.												1	-1	0	1	1	2
Rapeseed	5	His.												1	-1	0	1	1	2
Sunflower	5	His.												1	-1	0	1	1	2
Palmo-copal	6	His.												-1	-1	0	1	1	0
Wallaba	6	His.												1	-1	0	1	1	2
Trees	6	His.												1	-1	0	1	1	2
Shellac	6	His.												1	-1	0	-1	-1	-2
Tragacanth	7	His.												1	-1	0	1	0	1
Gum Arabic	7	His.												1	-1	0	1	0	1
Guar gum	7	His.												1	-1	0	1	1	2
Gum exudate	7	His.												1	-1	0	1	0	1

Appendix 3. Historic binders – Animal derivatives

Animal derivatives	Type of use	Function	Location	Score	Source
Fish oil	- Raw earth construction	Waterproofing	- Americas - Arctics	**0**	- Houben & Guillaud, 1994
Fat (ex. Hogs' lard, through Sodium Oleate)	- Mortar - Lime putty	Toughen, Setting performance, Water-repellent agent	- Roman Empire	**1**	- Maravelaki-Kalaitzaki et al, 2023 - Houben & Guillaud, 1994
Blood (ex. Bull, hippopotamus,)	- Rammed Earth - Adobe - Mortar - Adhesive - Binder - Raw earth construction	Toughen and setting performance, delay setting time. Chemical reaction with lime. Only fresh.	- Mediterranean - Germany - Roman Empire	**1**	- Van Gorp, 2018 - Ganotopoulou, 2014 - Maravelaki-Kalaitzaki et al, 2023 - Lehm people - Houben & Guillaud, 1994 - Zeng et al, 2008
Glue (ex. horn, bone, hooves, hides)	- Adhesive - Binder - Mortar - Renderings	Mechanical properties enhancement. Stabilisation.	- Rhodes - Roman Empire - China	**0**	- Maravelaki-Kalaitzaki et al, 2023 - Zeng et al, 2008 - Houben & Guillaud, 1994 - Langejans et al, 2022
Fish glue (ex. sturgeon bladder)	- Adhesive	Mechanical properties enhancement. Stabilisation.	- Arctic region - Egypt - Roman Empire	**0**	- Langejans et al, 2022
Hair/fur (Through keratin)	- Binder - Renderings - Raw earth construction	Stabilizing through fibres	- Egypt	**0**	- Maravelaki-Kalaitzaki et al, 2023 - Houben & Guillaud, 1994

Appendix 4. Historic binders – Animal produced

Animal produced	Type of use	Function	Location	Score	Source
Animal urine (ex. Horse urine)	- Adobe - Mortar - Daub	Replaces water. Chemical reaction with lime. Prevents cracking & erosion.	- Roman Empire	**2**	- Ganotopoulou, 2014 - Zeng et al, 2008 - Houben & Guillaud, 1994
Lime (derivative shells & coral)	- Raw earth construction	*No information.*	- Africa	**4**	- Houben & Guillaud, 1994
Egg, white (ex. Albumen)	- Mortar - Adhesive - Binder - Paint	toughen and setting performance, delay setting time	- South Asia - Egypt - Roman Empire	**3**	- Ramesh Babu, Neeraja, 2017 - Maravelaki-Kalaitzaki et al, 2023 - Zeng et al, 2008
Egg, yolk	- Adhesive - Binder	*No information.*	- Italy	**3**	- Maravelaki-Kalaitzaki et al, 2023 - Zeng et al, 2008
Dung, cow	- Rammed Earth - Adobe - Daub - Raw earth construction	Limited water resistance. Reduces compressive strength. Gains cohesion through fibre presence, phosphoric acid, potassium, elasticity	- Mediterranean - Germany - Africa	**1**	- Van Gorp, 2018 - Ganotopoulou, 2014 - Lehm people - Houben & Guillaud, 1994 - Dethier, 2020
Dung, camel	- Raw earth construction	Fibres & minerals, elasticity	- Middle East - Africa	**1**	- Ganotopoulou, 2014 - Houben & Guillaud, 1994
Dung, horse	- Raw earth construction	Fibres & minerals, elasticity	- Mediterranean	**1**	- Ganotopoulou, 2014 - Houben & Guillaud, 1994
Casein (Curdled milk)	- Adobe - Binder - Mortar - Raw earth construction	toughen and setting performance, stabilisation, combined with bull's blood.	- Egypt - Italy - Africa	**1**	- Ganotopoulou, 2014 - Maravelaki-Kalaitzaki et al, 2023 - Zeng et al, 2008 - Houben & Guillaud, 1994 - Langejans et al, 2022
Milk products (ex. Whey, powdered milk)	- Adhesive - Binder	*No information.*	- Europe	**1**	- Langejans et al, 2022
Beeswax	- Adhesive	Water proofing, workability, soften material	- Italy - Africa - Europe	**2**	- Langejans et al, 2022

Appendix 5. Historic binders – Plant based

Plant based	Type of use	Function	Location	Score	Source
Jaggery	- Mortar - Rammed Earth	cohesive strength	- South Asia	**3**	- Ramesh Babu, Neeraja, 2017
Molasses	- Adobe - Sandy soils - Silty soils	delay setting time, improves compressive strength, reduces capillarity. 5%	- Americas	**3**	- Ganotopoulou, 2014 - Houben & Guillaud, 1994
Sugar, refined	- Mortar	delay setting time, prevent shrinkage & cracking, cohesive strength and traction resistance in lime	- South Asia	**3**	- Ramesh Babu, Neeraja, 2017 - Maravelaki-Kalaitzaki et al, 2023 - Langejans et al, 2022
Kapok seed flour	- Raw earth construction	Paste of 20-25L/10kg, boil 6h.	- South Asia	**1**	- Houben & Guillaud, 1994
Rye dough	- Mortar	toughen and setting performance	- Roman Empire	**0**	- Maravelaki-Kalaitzaki et al, 2023
Starch (ex. potato, corn, cassava,	- Adhesive - Binder	Viscosity modifier, plasticizer, freezing–thawing durability		**3**	- Maravelaki-Kalaitzaki et al, 2023
Glutenous rice	- Adhesive - Binder - Mortar - Rammed Earth	*No information.*	- Japan - China	**3**	- Lubelli, 2018 - Zeng et al, 2008
Soy	- Adhesive	*No information.*	- Japan	**3**	- Langejans et al, 2022
Seaweed (powder or boiled)	- Adhesive - Binder	Increased workability, decreased durability	- Japan	**2**	- Lubelli, 2018
Beer	- Mortar	*No information.*	- Italy	**1**	- Zeng et al, 2008
Vegetable juice	- Mortar	*No information.*	- Italy	**0**	- Zeng et al, 2008
Keratin, plant	- Binder	*No information.*	- Egypt	**3**	- Maravelaki-Kalaitzaki et al, 2023
Tannin (ex. bark of néré, oak, chestnut, scorpioid acacia)	- Mortar	Improve coating sand by clay. Break-up lumps. Reduce permeability. Replaces water when used as decoctions.	- Italy	**3**	- Zeng et al, 2008 - Houben & Guillaud, 1994
Latex (ex. Euphorbia trees, hevea rubber)	- Adobe - Basic soils - Mortar	Reduces permeability. Improves plasticity and strength.	- Americas - Asia - Africa	**3**	- Ganotopoulou, 2014 - Houben & Guillaud, 1994 - Langejans et al, 2022
Plant mucilage (ex. Milk of Fig, banana leaves)	- Mortar	toughen and setting performance. Erosion resistance, slows water absorption.	- Egypt - Roman Empire	**5**	- Maravelaki-Kalaitzaki et al, 2023 - Zeng et al, 2008 - Houben & Guillaud, 1994
Cacti (ex. Prickly pear, powder or mucilage)	- Mortar - Plaster - Stucco floor	improves water and stress resistance, prevents cracking, and plasticity lime mortar	- Americas	**3**	- Maravelaki-Kalaitzaki et al, 2023 - Rampazzi et al, 2016
Agar (ex. Red seaweed)	- Adhesive	*No information.*	- Asia	**2**	- Langejans et al, 2022

Appendix 6. Historic binders – Ash

Ash	Type of use	Function	Location	Score	Source
Hardwood	- Raw earth construction	Stabilising through calcium carbonate. (5-10%) Dry compressive strength	- Asia	**1**	- Houben & Guillaud, 1994
Coconut shell	- Mortar	Dry compressive strength	- South Asia	**3**	- Ramesh Babu, Neeraja, 2017
Vegetable	- Adobe	Durability	- Middle East	**3**	- Ganotopoulou, 2014 - Langejans et al, 2022
Bone	- Mortar	Durability	- Europe	**1**	- Langejans et al, 2022

Appendix 7. Historic binders – Oils

Oils	Type of use	Function	Location	Score	Source
Coconut	- Adobe - Raw earth construction	*No information.*	- South Asia	**2**	- Ganotopoulou, 2014 - Houben & Guillaud, 1994
Cottonseed	- Adobe - Raw earth construction	*No information.*	- Americas	**2**	- Ganotopoulou, 2014 - Houben & Guillaud, 1994
Linseed	- Adobe - Mortar - Raw earth construction	Water-repellent agent, mechanical strength improvement, freezing–thawing durability, extreme weather condition durability	- Europe - Asia	**2**	- Ganotopoulou, 2014 - Maravelaki-Kalaitzaki et al, 2023 - Houben & Guillaud, 1994
Castor	- Adobe - Raw earth construction	Compressive strength	- Africa - Asia	**2**	- Ganotopoulou, 2014 - Houben & Guillaud, 1994
Saponified palm	- Renderings	Chemical reaction with lime. Stabilising.	- Africa	**2**	- Houben & Guillaud, 1994
Shea (also butter)	- Renderings	*No information.*	- Africa	**0**	- Houben & Guillaud, 1994
Olive	- Mortar	Water-repellent agent, mechanical strength improvement, freezing–thawing durability, extreme weather condition durability	- Mediterranean	**2**	- Maravelaki-Kalaitzaki et al, 2023
Sesame	- Mortar	Water-repellent agent	- Japan	**2**	- Lubelli, 2018
Rapeseed	- Mortar	Water-repellent agent	- Japan	**2**	- Lubelli, 2018
Sunflower	- Mortar	Water-repellent agent	- Japan	**2**	- Lubelli, 2018

Appendix 8. Historic binders – Resins

Resins	Type of use	Function	Location	Score	Source
Palmo-copal (derivative palm oil)	- Raw earth construction	Water permeability (3-8% sandy soils), solidifying moist soils	- South Asia	**0**	- Houben & Guillaud, 1994
Wallaba resin	- Raw earth construction - Moist soils	Water repellent, solidifying	- South America	**2**	- Houben & Guillaud, 1994
Trees (ex. Conifer trees; Scots pine, Norway spruce, Balsam fir, European Larch, Mastic)	- Raw earth construction - Mortar - Adhesive - Lacquers - Paint	Obtained in turpentine production. Soluble in organic solvents, forms gel with iron/aluminium. Reduces water absorption soil	- Europe - Africa - Australia - Americas - Asia	**2**	- Houben & Guillaud, 1994 - Langejans et al, 2022
Shellac (derivative lac bug ANIMAL)	- Adhesive - Varnish	Confers strength on sandy soils, not waterproof	- South Asia - Americas	**-2**	- Houben & Guillaud, 1994 - Langejans et al, 2022

Appendix 9. Historic binders – Gums

Gums	Type of use	Function	Location	Score	Source
Tragacanth	- Mortar	cohesive strength and traction resistance in lime	- Middle East	**1**	- Maravelaki-Kalaitzaki et al, 2023
Gum Arabic	- Mortar - Raw earth construction	Flocculant, dry compression strength, slows capillary absorption	- Africa	**1**	- Maravelaki-Kalaitzaki et al, 2023 - Houben & Guillaud, 1994
Guar gum	- Mortar	increase in viscosity & water-retention capacity, delay of setting time, freezing–thawing durability	- Africa - South Asia	**2**	- Maravelaki-Kalaitzaki et al, 2023
Gum exudate (derivative fruit trees)	- Stucco - Wall paintings	cohesive strength and traction resistance in lime	- Mediterranean - South America	**1**	- Langejans et al, 2022

Appendix 10. Mixture composition testing

Testing Round 1

3. Water content - Bar test

John Norton

- Aquire metal bar (500mm height, 10mm diameter).
- Prepare Rammed Earth mixture (ex. test 1).
- Squeeze Rammed Earth mixture with hands into 2x fist sized ball.
- Place Rammed Earth sample on the ground.
- Place bar on top of sample, hold in place with one hand.
- Let the bar sink due to own weight, do not push!
- Observe potential outcomes:

- Sinking of bar < 2cm
Feels dry -> Too dry -> add water -> repeat test
Feels wet -> Too high clay content -> add sand -> repeat test

- Sinking of bar > 2cm
Too wet -> leave to dry -> repeat test

- Sinking of bar = 2cm
Optimum water content -> suitable for use

- Continue to perform drop test during construction process, to prevent drying of Rammed Earth mixture whilst in use.

4. Shrinkage - Shrink box/Alcock test

SNZ4298 John Norton

- Construct simple wooden mould, with bottom but no top (Height 20mm, width 20mm, length 300mm).
- Prepare Rammed Earth mixture (ex. test 1).
- Lightly lubricate mould with low viscosity non-resin mineral oil.
- Pour the mixture in mould.
- Hit with flat faced and right angled tamper (10 times).
- Repeat until mould is full.
- Skim off excess mixture with palette knife and smooth surface.
- Cure mixture, in mould, in climate chamber (28 days).
- Compress any seperated material to one end of mould.
- Measure length of shrinkage gap inside mould.
- Linear shrinkage should stay below 3%, advisory to minimize linear shrinkage to 2%.
- If shrinkage is higher than 3%, composition mixture should be altered by using more clay or binder.
- Repeat testing until required results are obtained.

5. Plasticity - Sausage or cigar test

John Norton

- Form clay roll, sized with diameter aproximately that of a thumb, and length of 2-3x a thumb.
- Wet clay roll until damp but firm.
- Flatten roll between thumb and forefinger to a ribbon, sized about 2-2.5cm thick, and length of 20cm if possible.
- Place roll across palm of hand.
- Gently ease the end of the roll over the edge of hand.
- Continue until first breakage.
- Measure length of fallen clay:

- Long ribbon = > 15cm (Unsuitable for load-bearing construction)
Too much cohesion -> add sand -> repeat test

- Medium ribbon = 8-12cm (Suitable for building)
Short end of range -> compacted use; ex. Rammed Earth.
Long end of range -> uncompacted use; ex. mud bricks.

- short ribbon = < 8cm (Unsuitable for load-bearing construction)
Too little cohesion -> add clay -> repeat test

Mixture composition

1. Water content - Workability test

EN 1015-3

- Aquire truncated conical mould (60mm height, bottom diameter 100mm, top diameter 70mm, minimum 2mm wall thickness).
- Wipe mould and flow table with damp cloth until clean.
- Let mould and flow table dry.
- Lightly lubricate surfaces with low viscosity non-resin mineral oil.
- Place mould on center of flow table.
- Mix solid components (30s).
- Add liquid components and mix at low speed (90s).
- Remove from container walls and let mixture rest (90s).
- Mix at low speed (60s).
- Pour half of the mixture in mould on the flow table. Hold mould firmly onto flow table with one hand.
- Hit with flat faced and right angled tamper (10 times).
- Repeat until mould is full.
- Skim off excess mixture with palette knife.
- Wipe flow table around mould clean and dry.
- Wait and remove mould (15s).
- Drop flow table repeatedly (15 times).
- Measure diameter resulting sample, note down.
- If sample 15,2 cm to 17,8 cm, mixture composition has passed test.

2. Water content - Drop test

John Norton

- Prepare Rammed Earth mixture (ex. test 1).
- Squeeze Rammed Earth mixture with hands into fist sized ball.
- Put one arm straight out at shoulder level, with ball in hand.
- Drop soil ball onto smooth clean surface at ground level. (+/- 1,5m)
- Observe potential outcomes:

- Intact sample
  Feels dry -> Too dry -> add water -> repeat test
  Feels wet -> Too high clay content -> add sand -> repeat test

- Highly fragmented sample
  Too wet -> leave to dry -> repeat test

- Minimally fragmented sample
  Optimum water content -> suitable for use

- Continue to perform drop test during construction process, to prevent drying of Rammed Earth mixture whilst in use.

3. Water content - Bar test

John Norton

- Aquire metal bar (500mm height, 10mm diameter).
- Prepare Rammed Earth mixture (ex. test 1).
- Squeeze Rammed Earth mixture with hands into 2x fist sized ball.
- Place Rammed Earth sample on the ground.
- Place bar on top of sample, hold in place with one hand.
- Let the bar sink due to own weight, do not push!
- Observe potential outcomes:

- Sinking of bar < 2cm
  Feels dry -> Too dry -> add water -> repeat test
  Feels wet -> Too high clay content -> add sand -> repeat test

- Sinking of bar > 2cm
  Too wet -> leave to dry -> repeat test

- Sinking of bar = 2cm
  Optimum water content -> suitable for use

- Continue to perform drop test during construction process, to prevent drying of Rammed Earth mixture whilst in use.

Appendix 11. Mechanical properties testing

Testing Round 2

8. Penetration & impact test
Houben & Guillaud

- Form compressed earth brick sample group (CEB).
- Weigh and note each sample, making sure to number samples.
- Dry samples further.
- Repeat weighing samples until no further reduction is noted.
- Aquire sharp probe.
- Push probe in samples from a distance of 5 to 10cm at a force of 1.5kg.
- Compare to predetermined acceptability norms.

- Form compressed earth brick sample group (CEB).
- Weigh and note each sample, making sure to number samples.
- Dry samples further.
- Repeat weighing samples until no further reduction is noted.
- Hold two samples perpendicular to each other.
- Hit both samples against each other, increasing force with each hit.
- The hardness of material can be estimated in relation to the sound produced by the hits.

9. Simple strength test
John Norton

- Form compressed earth brick sample group (CEB).
- Aquire two supports, place them on surface and space them (300mm).
- Place CEB over both supports, making sure the CEB does not touch the surface at ground level.
- Apply pressure to CEB by standing on the block with one foot.
- Use an average weighted male (80-90kg in Netherlands).
- If brick breaks in half, alter soil mixture composition, repeat test.

10. Modulus of rupture test
John Norton

- Form compressed earth brick sample group (CEB).
- Aquire three steel bars, place two of them parallel on a surface and space them (250mm).
- Apply pressure evenly on CEB surface, using third steel bar, spaced evenly between surface level bars.
- Record weight or pressure at which CEB breaks.
- Repeat test with 5 samples for correct average.
- Calculate modulus of rupture using:

$$M = \frac{(1.5 \times 250mm \times kg\ pressure)}{(CEB\ width \times CEB\ height^2)}$$

Mechanical characteristics

6. Wetting and drying test

Houben & Guillaud

- Form compressed earth brick sample group (CEB).
- Weigh and note each sample, making sure to number samples.
- Dry samples further.
- Repeat weighing samples until no further reduction is noted.
- Store samples in extremely moist environment (7 days).
- Immerse samples in water equal to the room temperature (5h).
- Remove from water and dry samples in oven at 70 degrees (42h).
- Remove samples from oven.
- Brush each sample using a metallic fibre brush on all surfaces.
- Remove parts of material affected from wetting and drying from brush fibres to have a consistent brushing surface.
- Force applied while brushing needs to be 1.5kg.
- Brush from top to bottom as well as from bottom to top.
- Brush each side 18 to 25 times.
- Once brushing is completed, one 48h cycle has finished.
- Repeat process for 12 complete cycles.
- Dry samples at 110 degrees until constant weight is observed.
- Compare weigth after wetting and drying tests to starting weight samples.

7. Abrasion test

Houben & Guillaud

- Form compressed earth brick sample group (CEB).
- Weigh and note each sample, making sure to number samples.
- Dry samples further.
- Repeat weighing samples until no further reduction is noted.
- Brush samples using a weighted metal brush (6kg).
- Brush surface that in construction use would be exposed to weathering conditions.
- One back and forth motion of the brush can be considered one cycle of abrasion.
- Repeat for 50 cycles of abrasion on weathering exposed side.
- Make sure to collect all debris that detaches from each sample.
- Weigh total collected debris for each sample.
- Calculate dry weight of debris per square cm of brushed surface, to relate test results independently to the sample size.
- Compare to standardised guidelines for abrasion tests, regarding CEB as well as fired bricks.

8. Penetration & impact test

Houben & Guillaud

- Form compressed earth brick sample group (CEB).
- Weigh and note each sample, making sure to number samples.
- Dry samples further.
- Repeat weighing samples until no further reduction is noted.
- Aquire sharp probe.
- Push probe in samples from a distance of 5 to 10cm at a force of 1.5kg.
- Compare to predetermined acceptability norms.

- Form compressed earth brick sample group (CEB).
- Weigh and note each sample, making sure to number samples.
- Dry samples further.
- Repeat weighing samples until no further reduction is noted.
- Hold two samples perpendicular to each other.
- Hit both samples against each other, increasing force with each hit.
- The hardness of material can be estimated in relation to the sound produced by the hits.

Appendix 12. Weathering testing

Testing Round 3

13. Moisture absorption test

John Norton

- Form compressed earth brick sample group (CEB) of 5, minimizing sizing of blocks to speed up production processes.
- Weigh and note each sample, making sure to number samples.
- Dry samples further.
- Repeat weighing samples until no further reduction is noted.
- Immerse samples in water, obtaining constant saturation (7 days).
- Weigh and note each sample, making sure to number samples.
- Calculate absorption in percentage wet to dry weight:

  - Absorption percentage = maximum 2 - 3 %
  Material suitable for construction.

  - Absorption percentage = maximum 4 %
  Material suitable for construction in wet regions.

- Alternatively measure samples by dry dimensions.
- Repeat moisture absorption test as described above.
- Measure samples by wet dimensions.
- Maximum expansion should be at most 0.2% for stabilized compressed blocks, 0.1% for in-situ Rammed Earth.

14. Freeze - thaw test

Houben & Guillaud

- Form compressed earth brick sample group (CEB), minimizing sizing of blocks to speed up production processes.
- Weigh and note each sample, making sure to number samples.
- Dry samples further.
- Repeat weighing samples until no further reduction is noted.
- Store samples in extremely moist environment (7 days).
- Place samples on aborbent material, saturated by water.
- Place samples on wetted material in freezer (max. -20 degrees).
- Remove from freezer (after 24h).
- Thaw samples in moist environment at 21 degrees (23h).
- Remove from moist environment.
- Brush firmly on each surface of the sample with metallic fibres to remove all affected areas of the material.
- Repeat test for 12 free-thaw cycles, return to absorbant material between each round.
- If test are to be interupted, samples must be kept in refrigerator.
- When completed, dry samples in oven (110 degrees) until constant weight is obtained.
- Calculate weight loss in regards to starting weight of samples.

15. Outside observation

- Form compressed earth brick sample group (CEB) of 5, minimizing sizing of blocks to speed up production processes.
- Weigh and note each sample, making sure to number samples.
- Dry samples further.
- Repeat weighing samples until no further reduction is noted.
- Place samples outside in a dedicated location, making sure to code each sample correctly.
- Location must be unsheltered and unobstructed by obstacles.
- Wind directions must be noted. Place identical samples in each wind directions.
- Return to location every second day.
- Note and document visual changes to the material.
- Note and document tactile changes to the material.
- Continue for a period of 30 days.
- Retrieve samples, making sure to code each sample correctly.
- Conduct previously done test on the now weathered material.
- Compared observations and test results to norms on weathering.

Weathering

John Norton

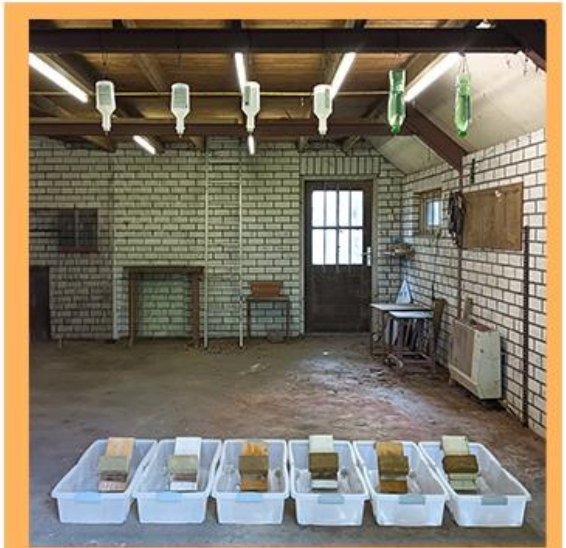
11. Water erosion resistance - Drip test

- Form compressed earth brick sample group (CEB).
- Let CEB completely dry in mould.
- Place CEB on an engineerd support board at an angle (45 degree).
- Place large water container at an elevation above board (2.5m).
- Aquire cotton string with length 2.5xdepth of water container.
- Saturate cotton string with water.
- Place string in water container, one end hanging above sample.
- Make sure the string drops water on CEB sample.
- Start timer.
- Stop timer when a hole has appeared in CEB sample:

- Measured time = 1 - 2 hours
Material suitable for dry areas; short (potentially violent) storms.

- Measured time = 6 - 8 hours
Material suitable for areas prolonged rain, over several hours.

- Measured time = > 24 hours
Material suitable for areas persistent rainfall, one or more days.



John Norton

12. Water erosion resistance - Spray test

- Form compressed earth brick sample group (CEB).
- Aquire shower head (100mm diameter).
- Make set up of shower head at a distance to sample (180mm).
- Spray whole sample with pressure of 1.4 kg/cm^2 (2 hours).
- Observe results on CEB sample:

- Pitting = 6 - 12 mm
Material suitable for areas with short infrequent storms.

- Pitting = 0 - 6 mm
Material suitable for areas with 500-1250 mm rainfall per annum.

- Pitting = 0 mm
Material suitable for areas >1250 mm rainfall per annum.

- More rigorous tests results can be aquired by spraying for 6 hours, applying the same standards mentioned above.
- Repeat test 5 times to establish average results.
- Failing material composition will need mixture compostion alteration or will require regular maintenance.

John Norton

13. Moisture absorption test

- Form compressed earth brick sample group (CEB) of 5, minimizing sizing of blocks to speed up production processes.
- Weigh and note each sample, making sure to number samples.
- Dry samples further.
- Repeat weighing samples until no further reduction is noted.
- Immerse samples in water, obtaining constant saturation (7 days).
- Weigh and note each sample, making sure to number samples.
- Calculate absorption in percentage wet to dry weight:

- Absorption percentage = maximum 2 - 3 %
Material suitable for construction.

- Absorption percentage = maximum 4 %
Material suitable for construction in wet regions.

- Alternatively measure samples by dry dimensions.
- Repeat moisture absorption test as described above.
- Measure samples by wet dimensions.
- Maximum expansion should be at most 0.2% for stabilized compressed blocks, 0.1% for in-situ Rammed Earth.

Appendix 13. Wetting and drying test – Images

Red – Yellow – Blue – White – Striped/**Black**
Albumen: Liquid – Sugar: 2% – Sugar: 5% – Cement – Albumen: Solid

Cycle 1 - 5 hours water submerging

Red – Yellow – Blue – White – Striped/**Black**
Albumen: Liquid – Sugar: 2% – Sugar: 5% – Cement – Albumen: Solid

Cycle 2 - 10 hours water submerging

Red – Yellow – Blue – White – Striped/**Black**
Albumen: Liquid – Sugar: 2% – Sugar: 5% – Cement – Albumen: Solid

Cycle 3 - 15 hours water submerging

Red – Yellow – Blue – White – Striped/**Black**
Albumen: Liquid – Sugar: 2% – Sugar: 5% – Cement – Albumen: Solid

Cycle 4 - 20 hours water submerging

Red – Yellow – Blue – White – Striped/**Black**
Albumen: Liquid – Sugar: 2% – Sugar: 5% – Cement – Albumen: Solid

Cycle 5 - 25 hours water submerging

Red – Yellow – Blue – White – Striped/**Black**
Albumen: Liquid – Sugar: 2% – Sugar: 5% – Cement – Albumen: Solid

Cycle 6 - 30 hours water submerging

Red – Yellow – Blue – White – Striped/**Black**
Albumen: Liquid – Sugar: 2% – Sugar: 5% – Cement – Albumen: Solid

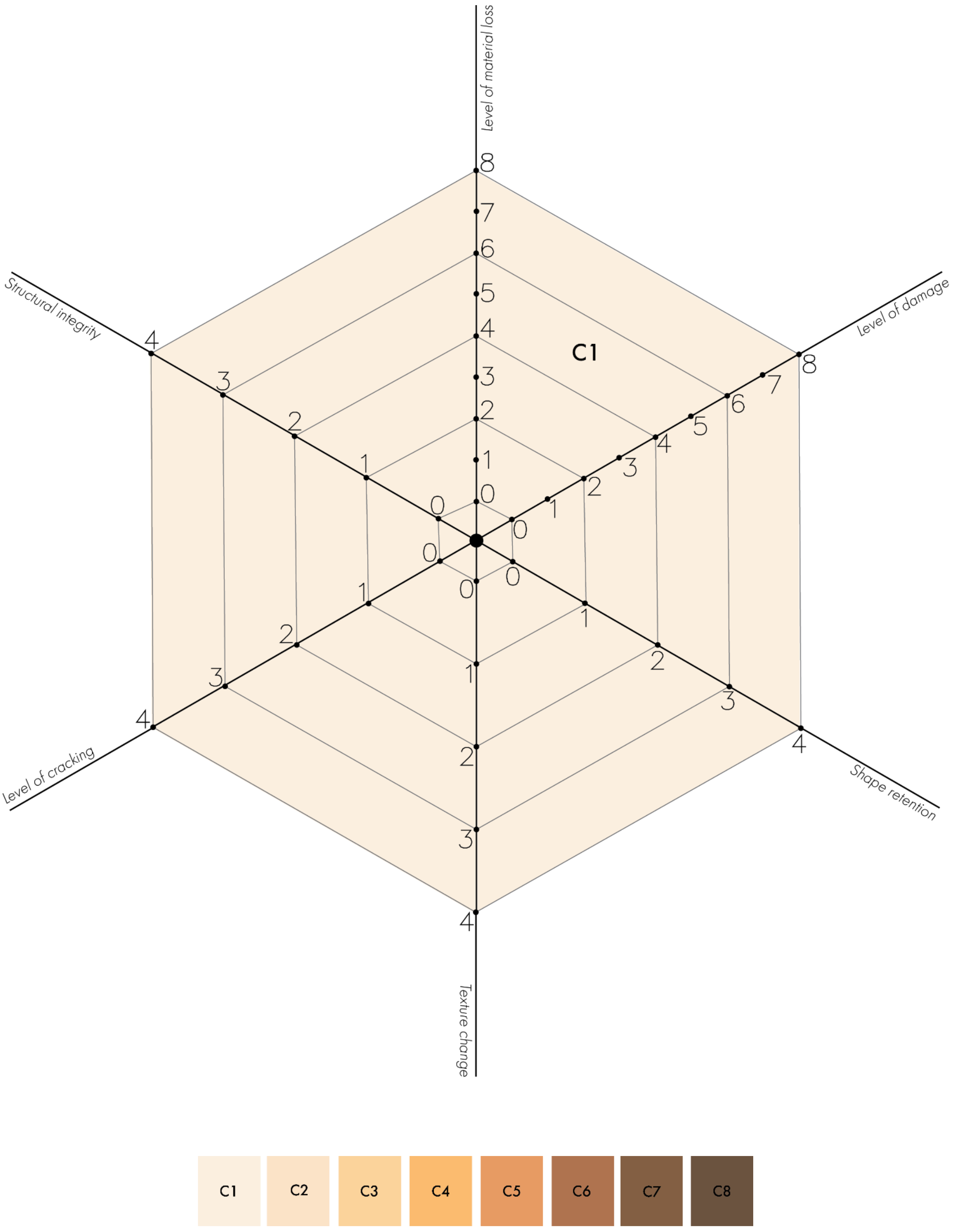
Cycle 7 - 35 hours water submerging

Red – Yellow – Blue – White – Striped/**Black**
Albumen: Liquid – Sugar: 2% – Sugar: 5% – Cement – Albumen: Solid

Cycle 8 - 40 hours water submerging

Appendix 14. Wetting and drying test – Results

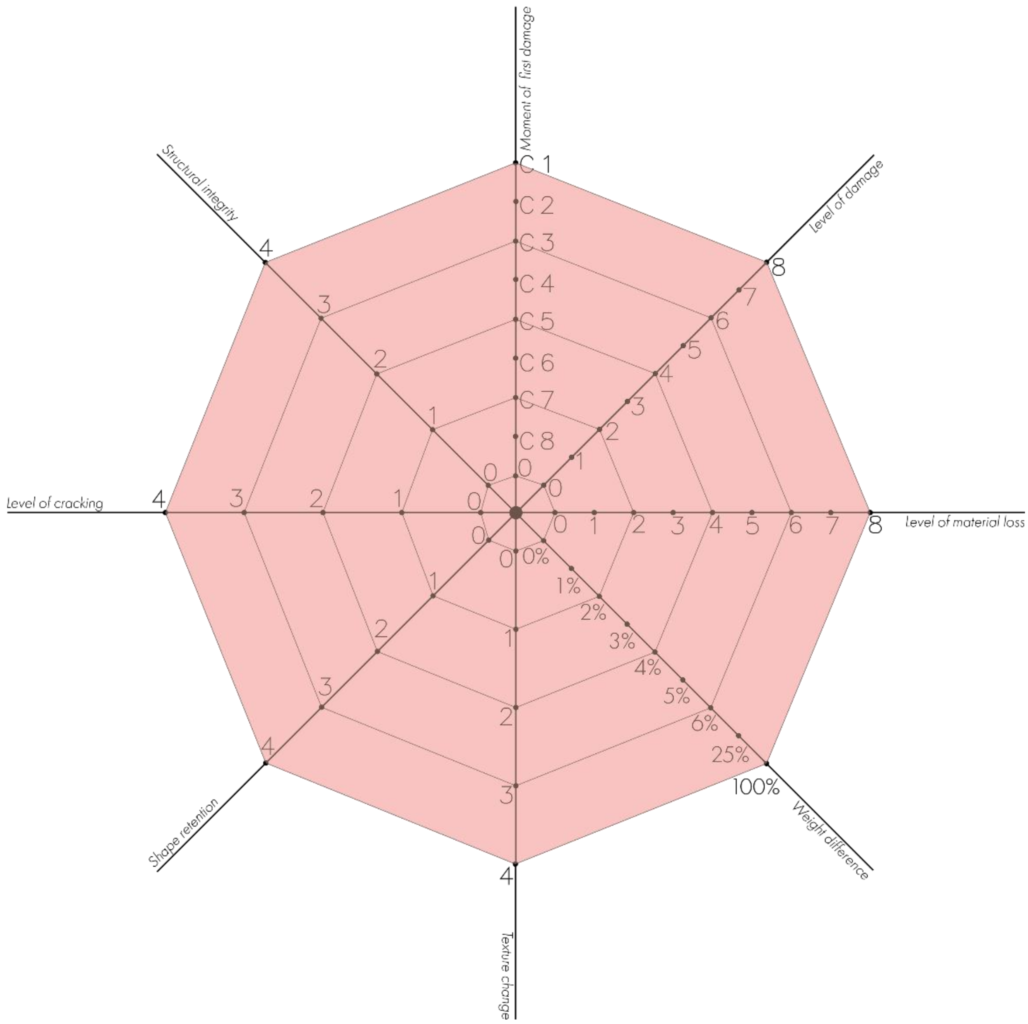
Interpretation regular, all samples

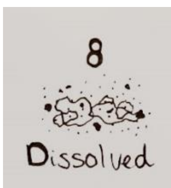


Final findings: Regular, all samples

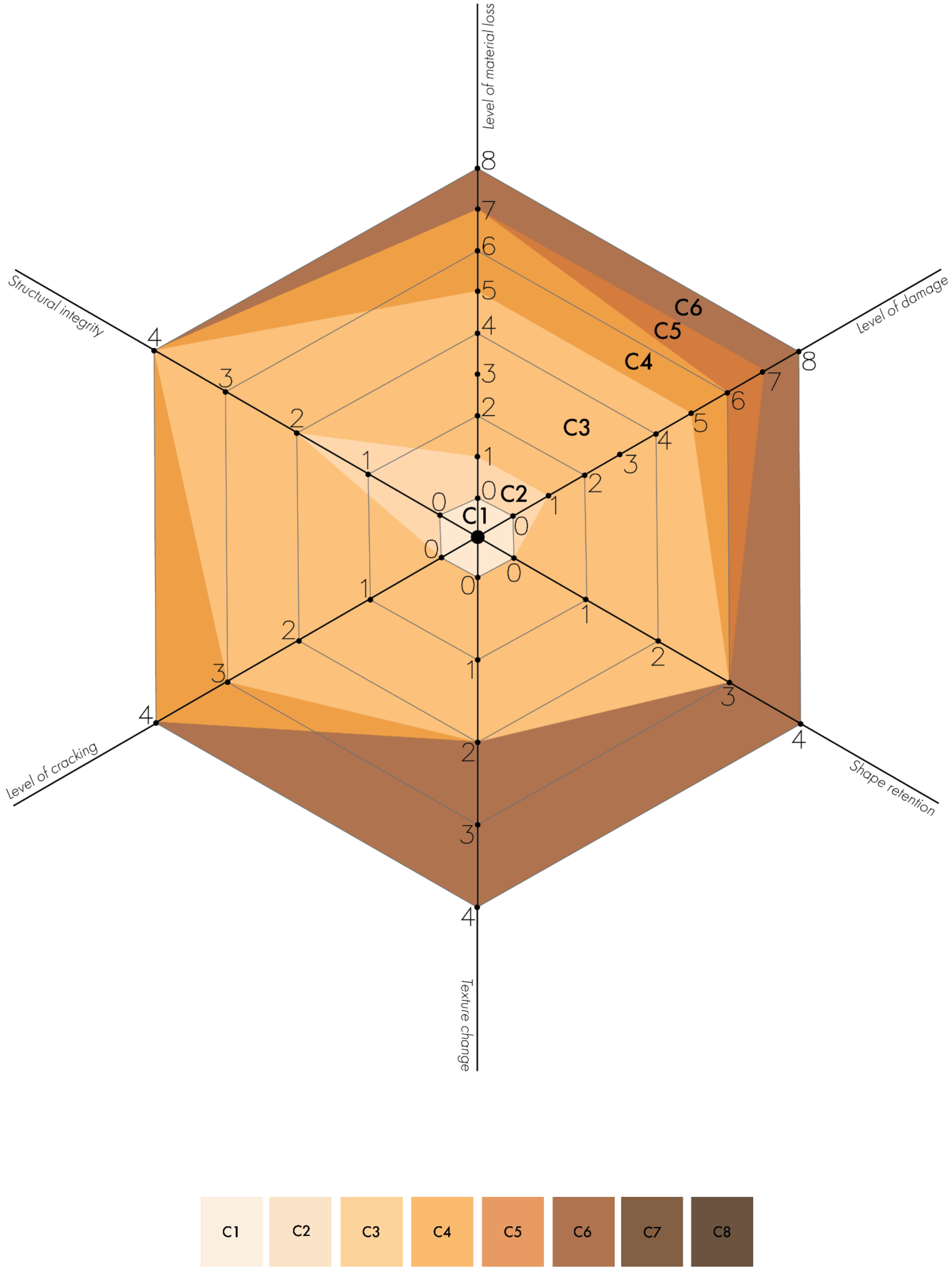
Final findings

Sample number: 1, 2, 3
Sample type: Regular



Category	Score	Visualisation
1. Moment of first damage	C1 = 8/8	
2. Level of damage	8/8	
3. Level of material loss	8/8	
4. Weight difference	100% = 8/8	
5. Texture change	4/4	
6. Shape retention	4/4	
7. Level of cracking	4/4	
8. Structural integrity	4/4	
Total	48/48	

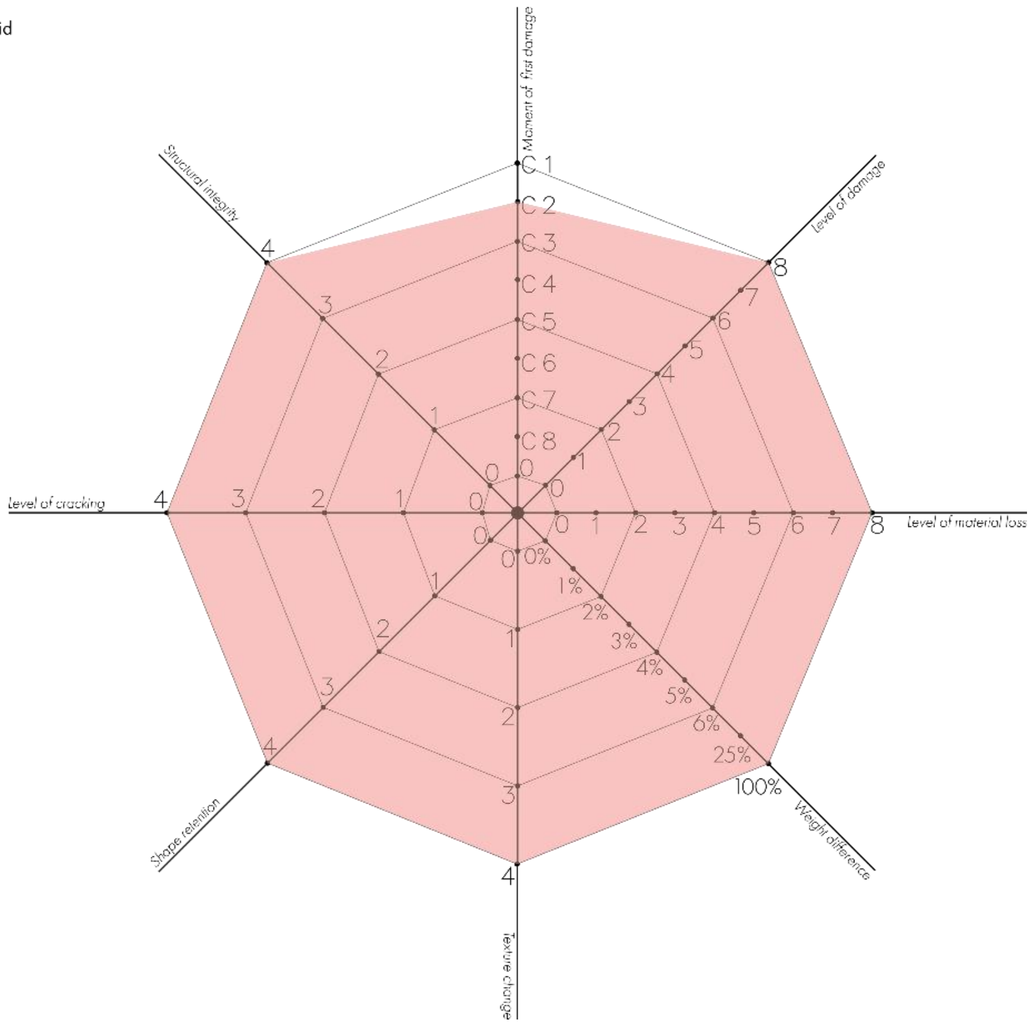
Interpretation albumen liquid, sample 1



Final findings: Albumen liquid, sample 1

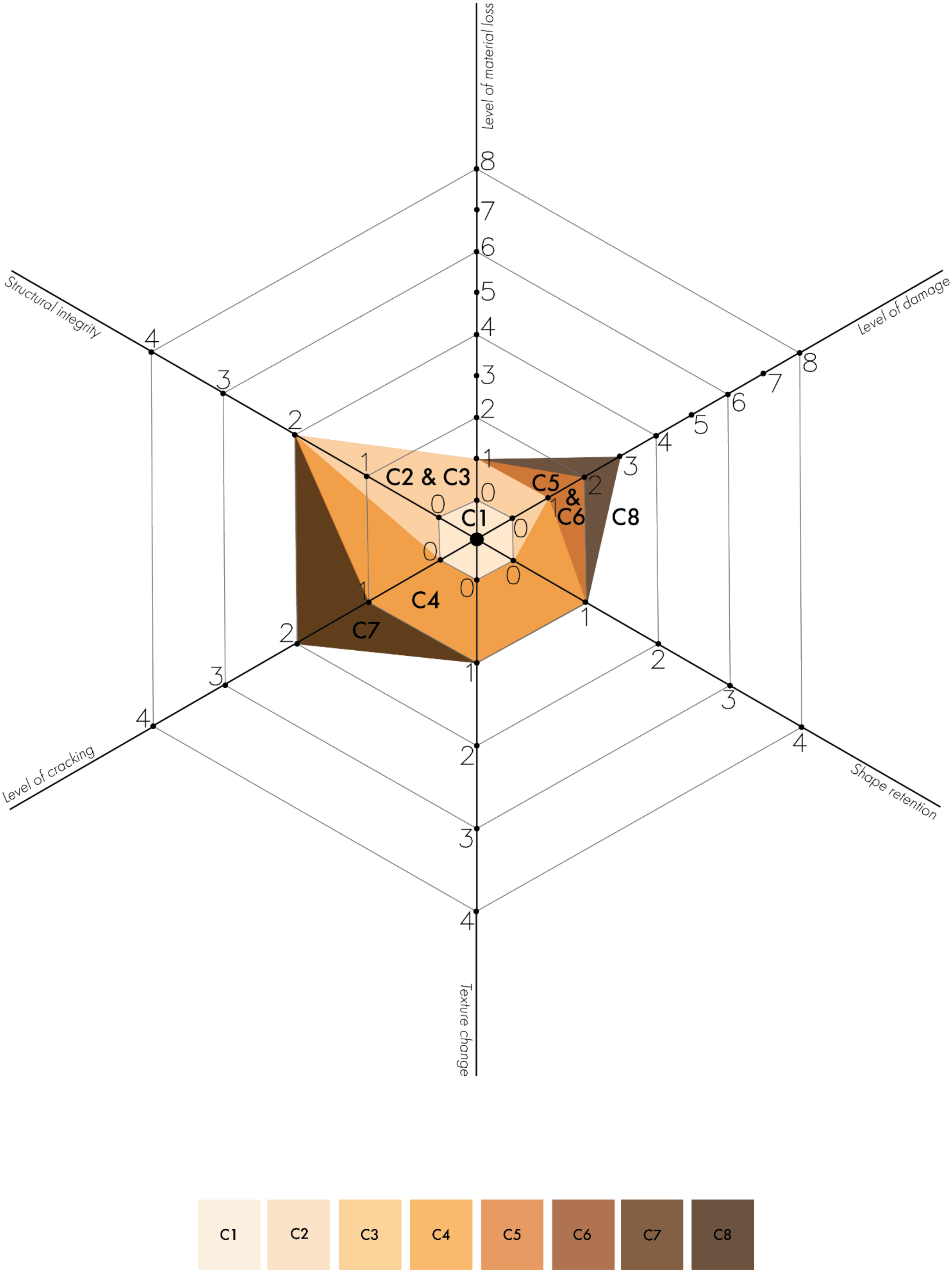
Final findings

Sample number: 1
Sample type: Albumen, liquid



Category	Score	Visualisation
1. Moment of first damage	C2 = 7/8	
2. Level of damage	8/8	
3. Level of material loss	8/8	
4. Weight difference	100% = 8/8	
5. Texture change	4/4	
6. Shape retention	4/4	
7. Level of cracking	4/4	
8. Structural integrity	4/4	
Total	47/48	

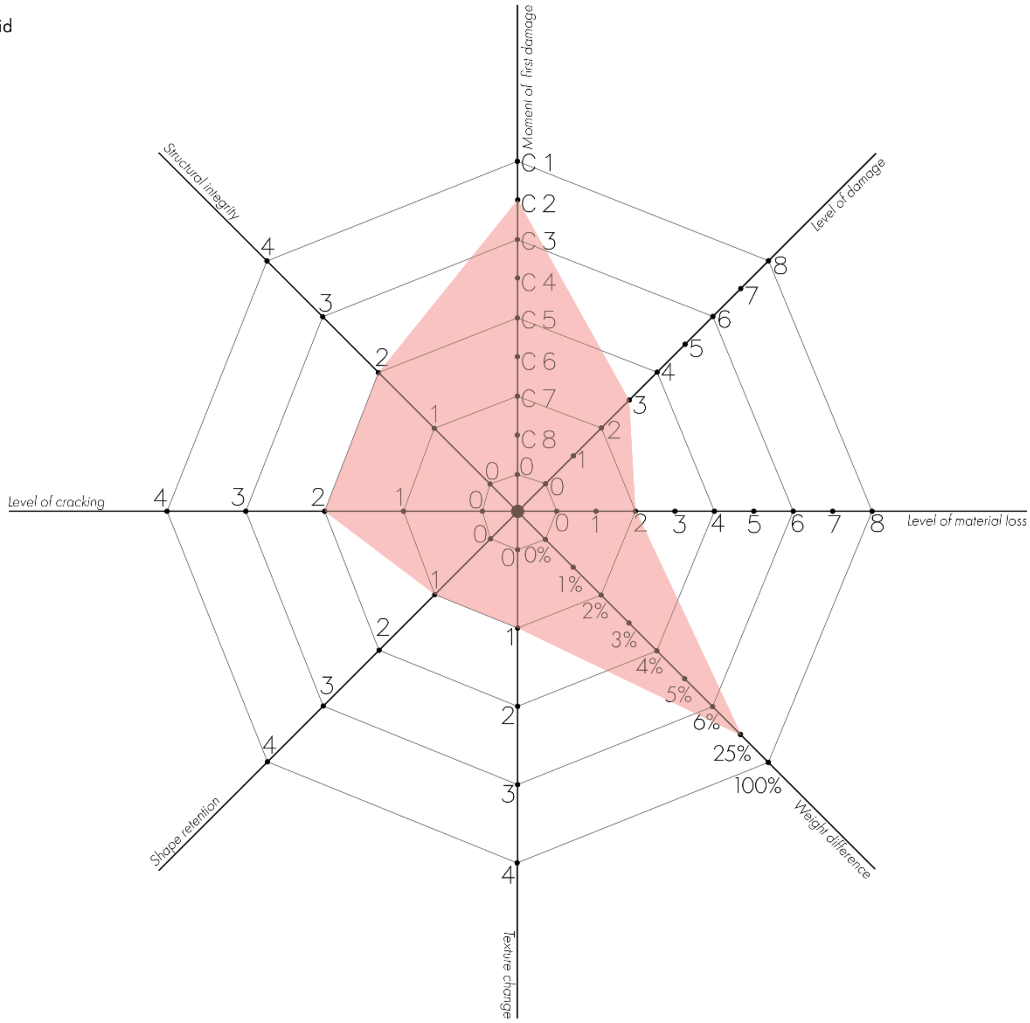
Interpretation albumen liquid, sample 2

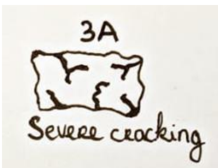
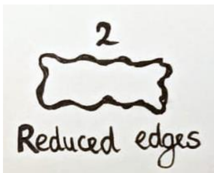


Final findings: Albumen liquid, sample 2

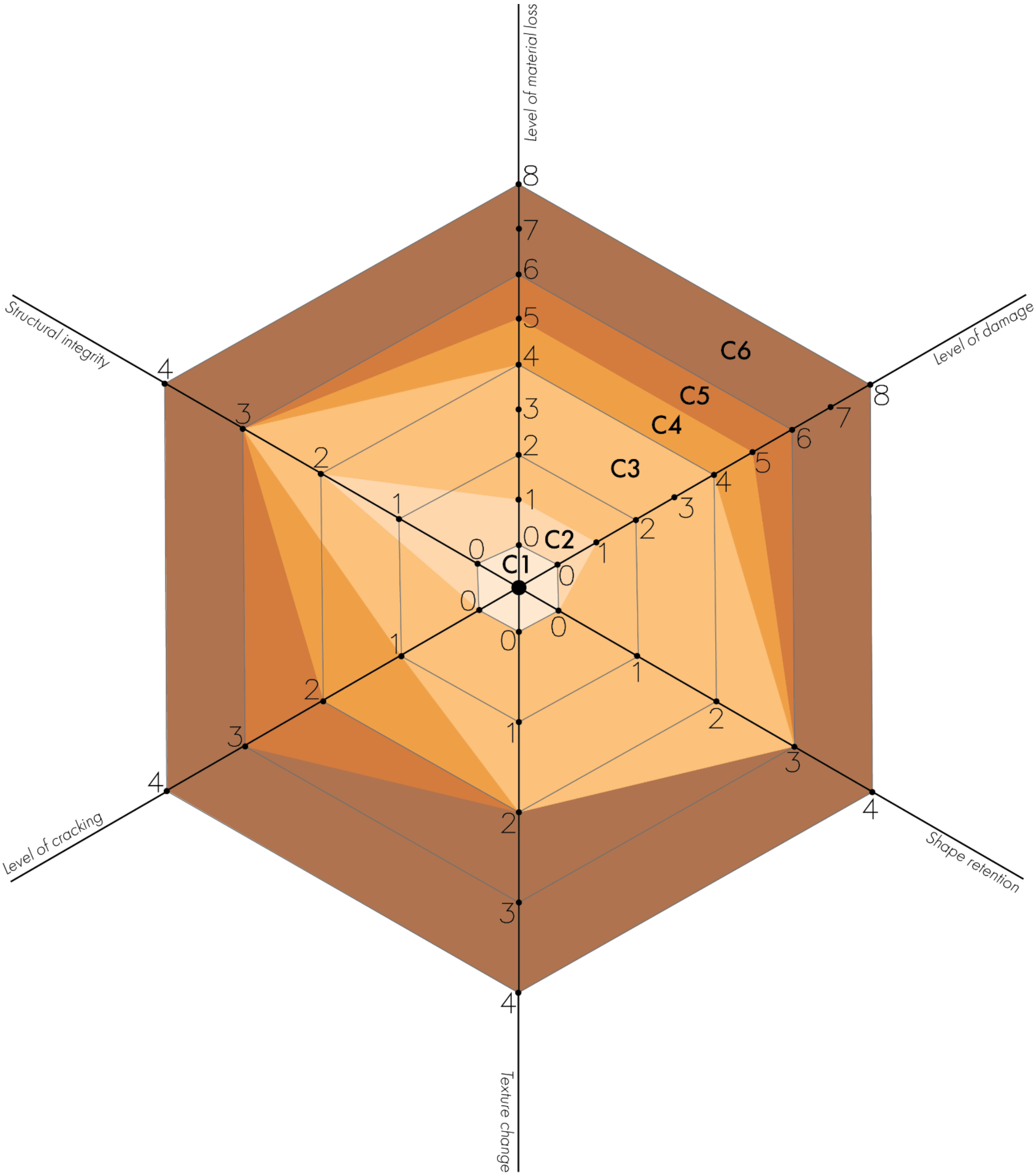
Final findings

Sample number: 2
Sample type: Albumen, liquid



Category	Score	Visualisation
1. Moment of first damage	C2 = 7/8	
2. Level of damage	3/8	2.  3.  5. 
3. Level of material loss	2/8	
4. Weight difference	28.5% = 7/8	
5. Texture change	1/4	
6. Shape retention	1/4	6.  7.  8. 
7. Level of cracking	2/4	
8. Structural integrity	2/4	
Total	25/48	

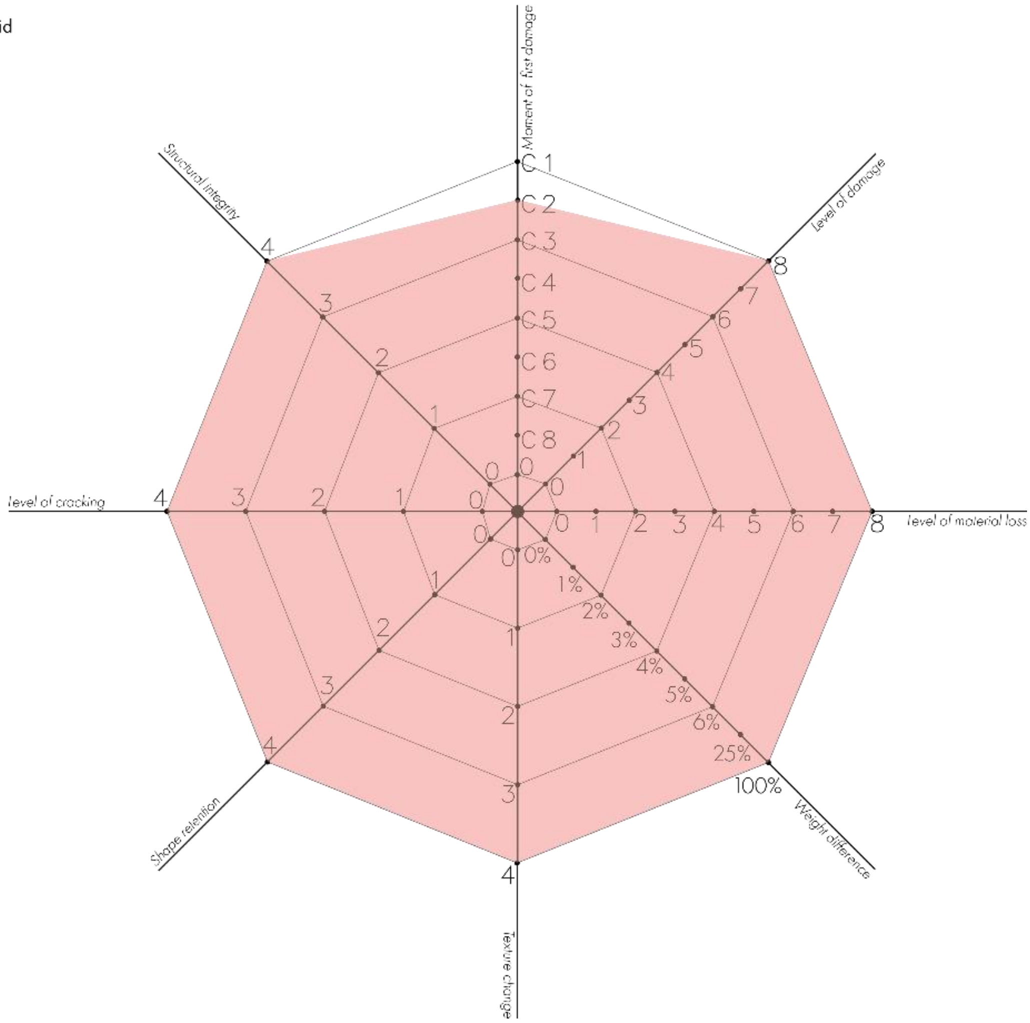
Interpretation albumen liquid, sample 3



Final findings: Albumen liquid, sample 3

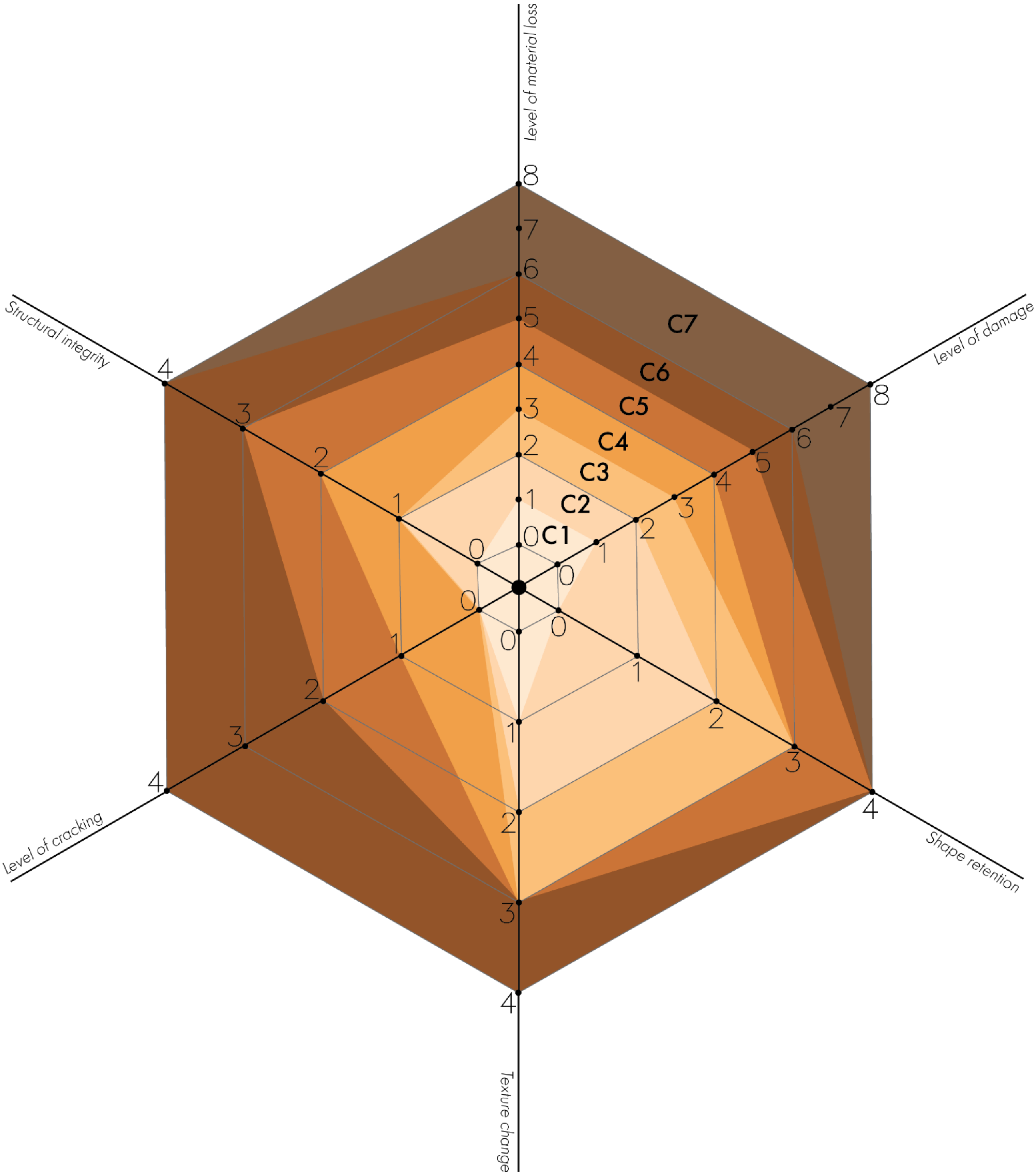
Final findings

Sample number: 3
Sample type: Albumen, liquid



Category	Score	Visualisation
1. Moment of first damage	C2 = 7/8	
2. Level of damage	8/8	
3. Level of material loss	8/8	
4. Weight difference	100% = 8/8	
5. Texture change	4/4	
6. Shape retention	4/4	
7. Level of cracking	4/4	
8. Structural integrity	4/4	
Total	47/48	

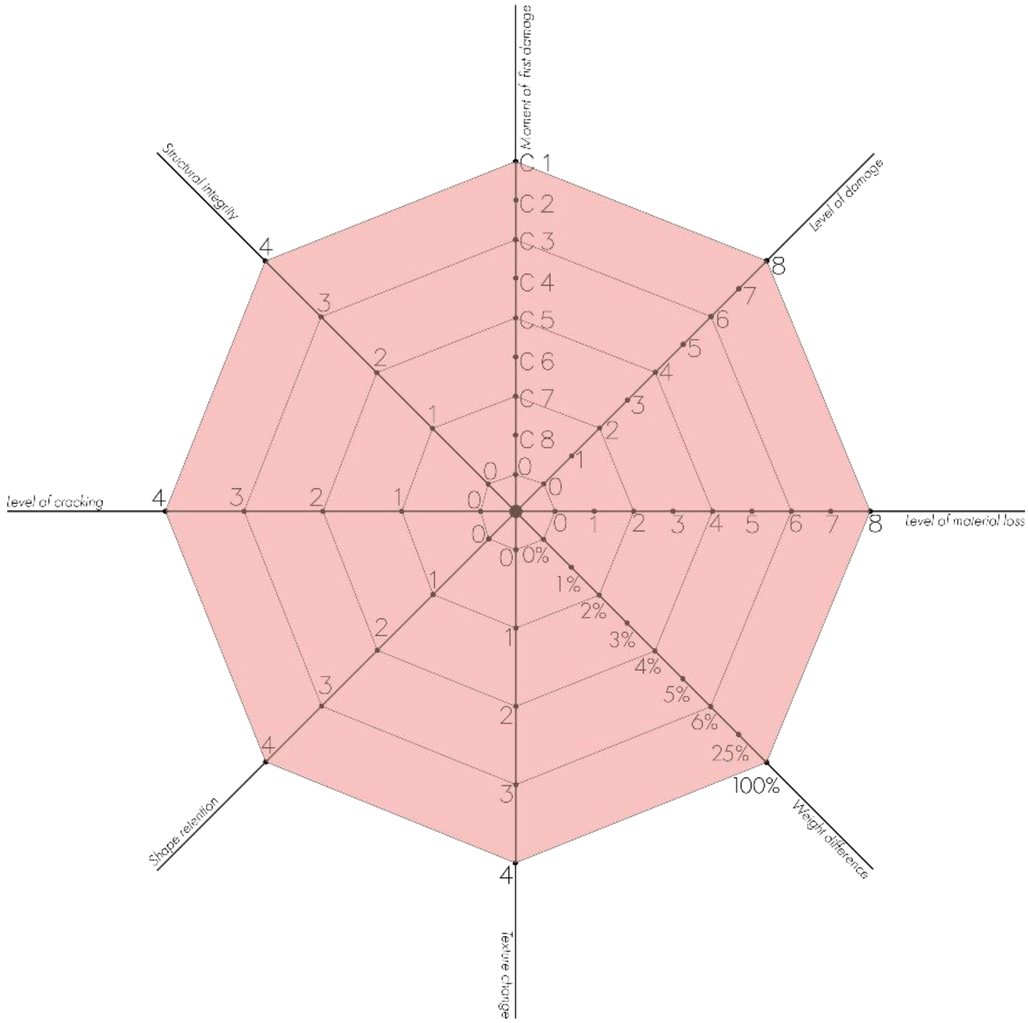
Interpretation sugar 2%, sample 1



Final findings: Sugar 2%, sample 1

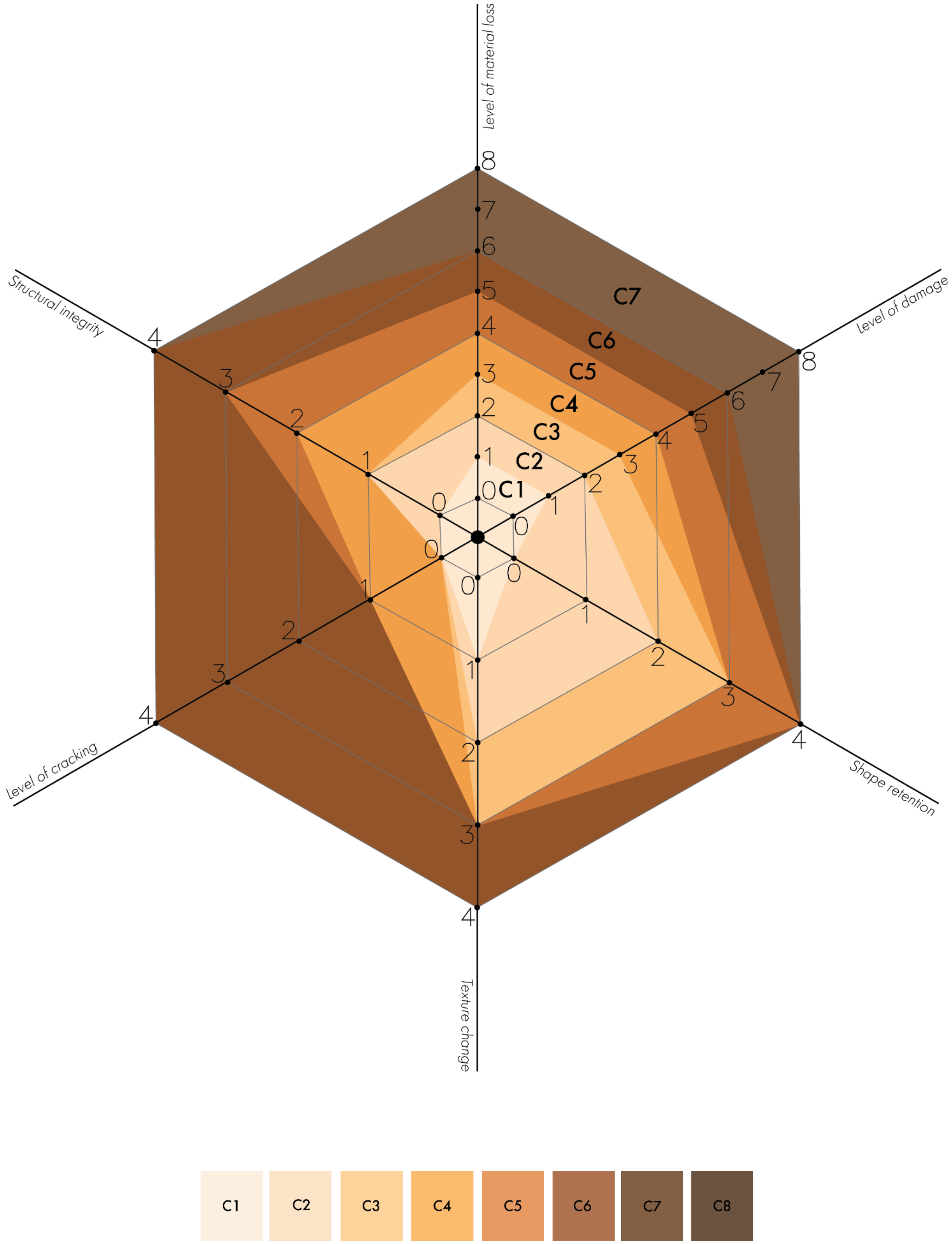
Final findings

Sample number: 1, 2, 3
Sample type: Sugar, 2%



Category	Score	Visualisation
1. Moment of first damage	C1 = 8/8	
2. Level of damage	8/8	
3. Level of material loss	8/8	
4. Weight difference	100% = 8/8	
5. Texture change	4/4	
6. Shape retention	4/4	
7. Level of cracking	4/4	
8. Structural integrity	4/4	
Total	48/48	

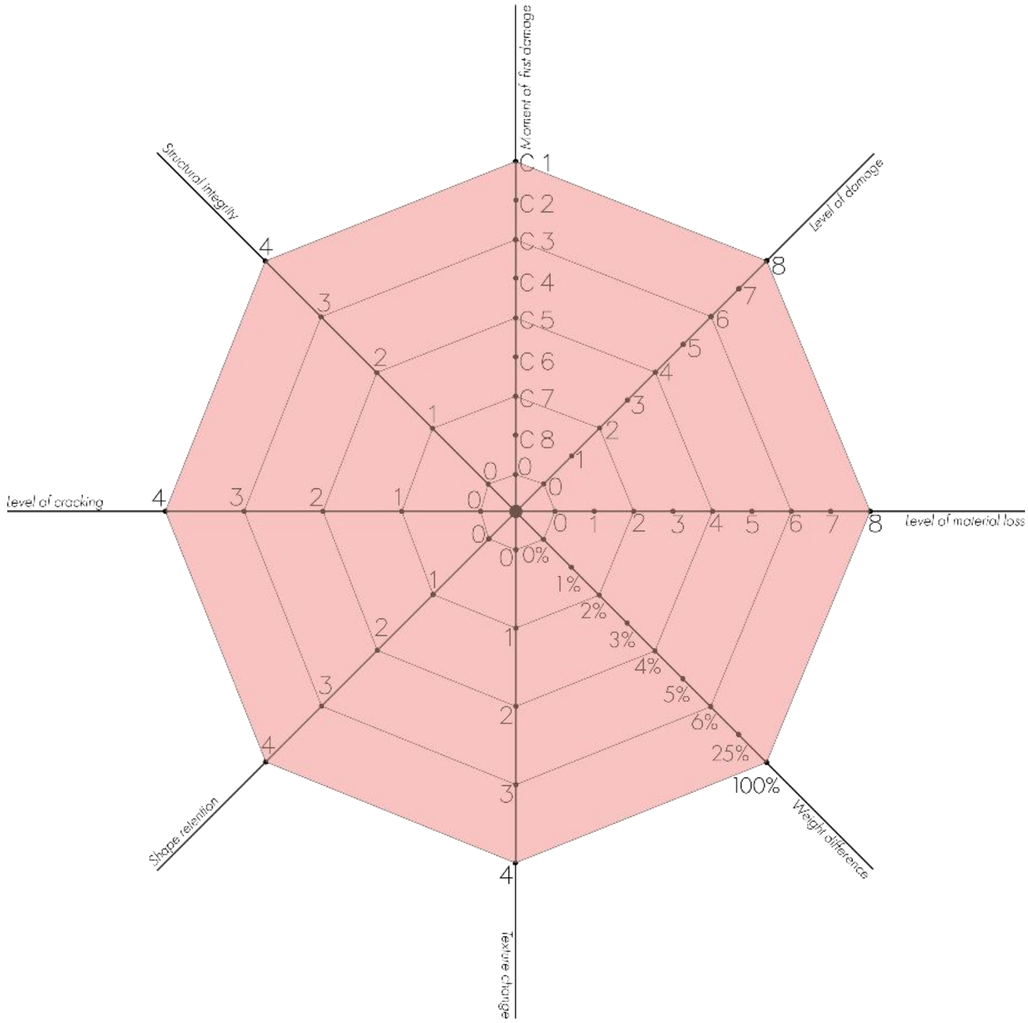
Interpretation sugar 2%, sample 2



Final findings: Sugar 2%, sample 2

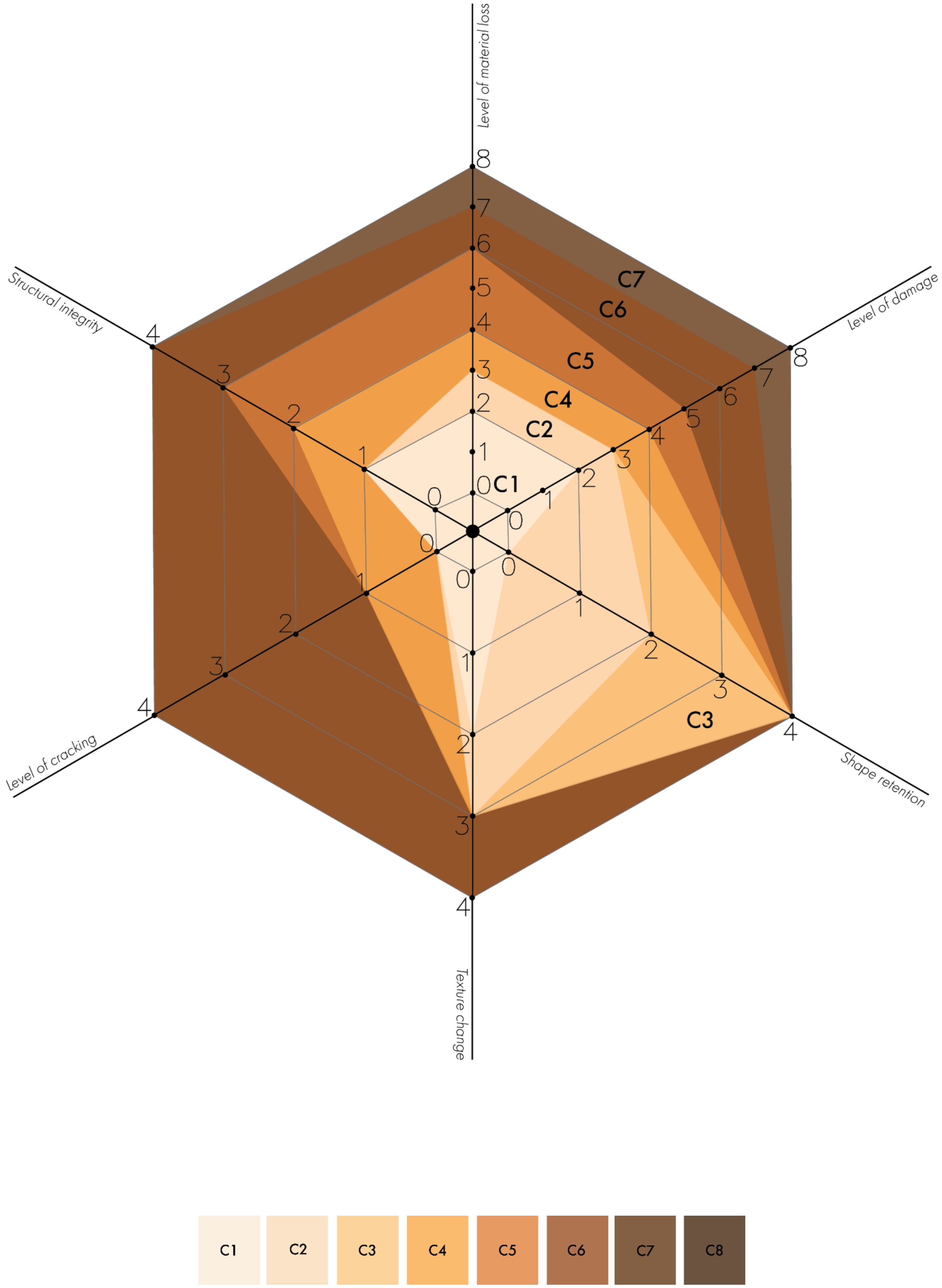
Final findings

Sample number: 1, 2, 3
Sample type: Sugar, 2%



Category	Score	Visualisation
1. Moment of first damage	C1 = 8/8	
2. Level of damage	8/8	
3. Level of material loss	8/8	
4. Weight difference	100% = 8/8	
5. Texture change	4/4	
6. Shape retention	4/4	
7. Level of cracking	4/4	
8. Structural integrity	4/4	
Total	48/48	

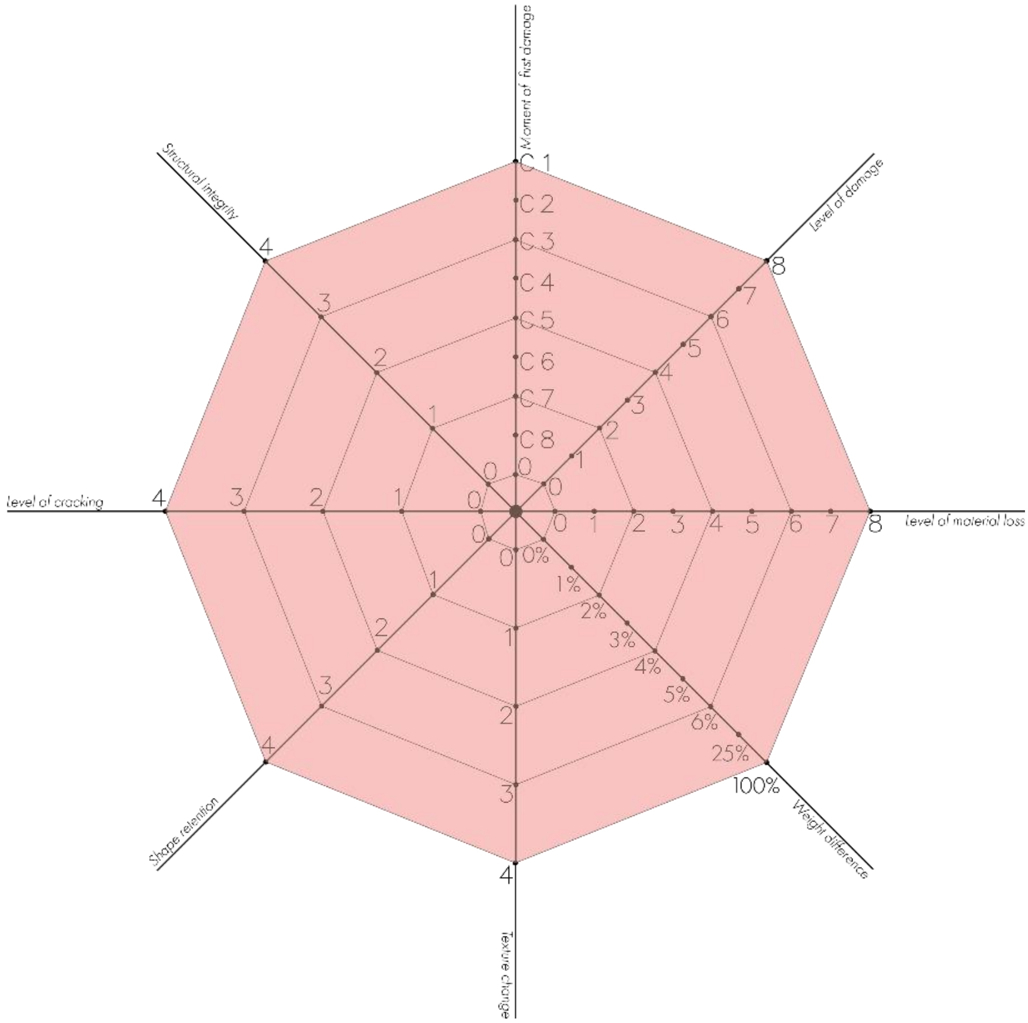
Interpretation sugar 2%, sample 3



Final findings: Sugar 2%, sample 3

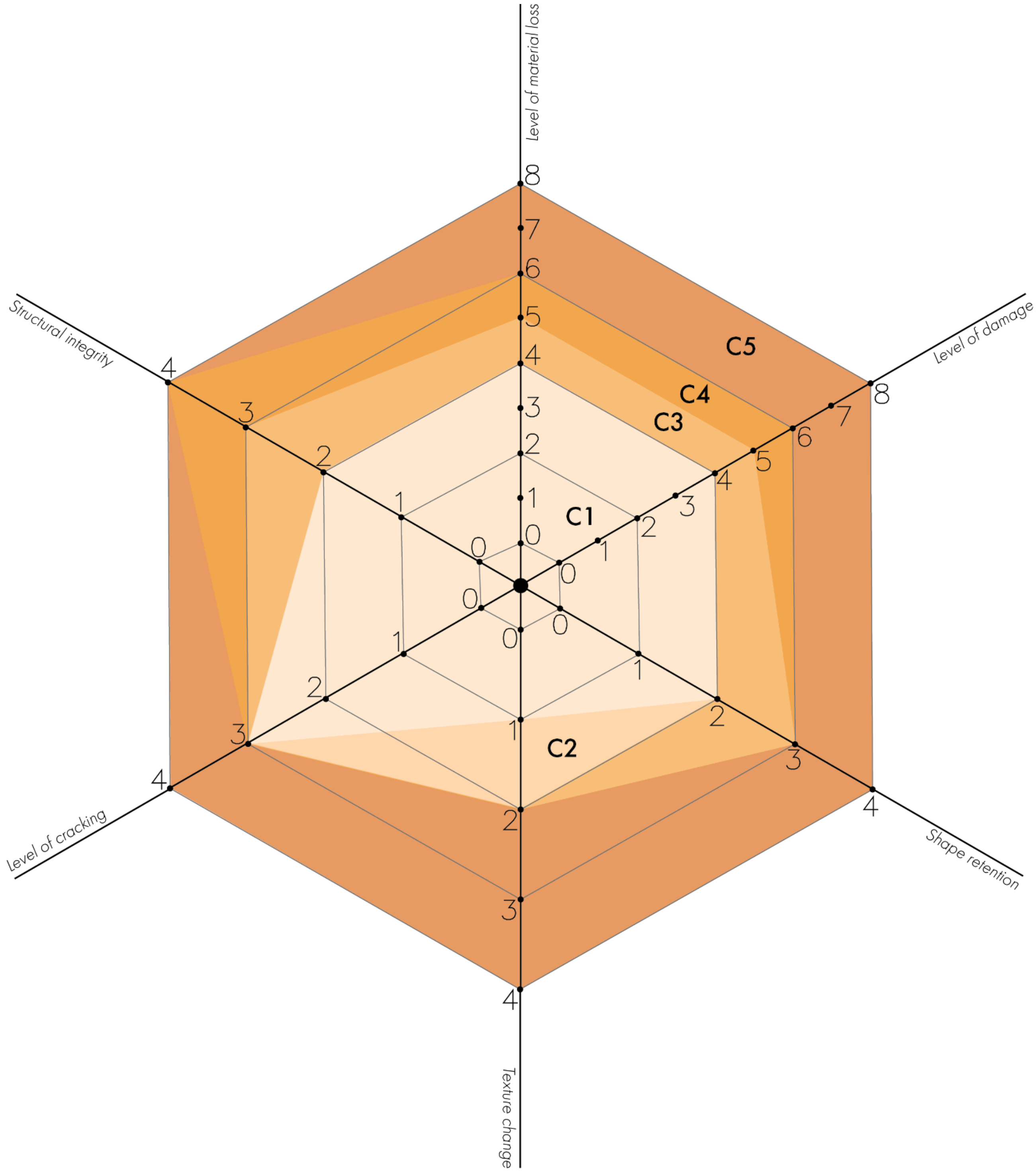
Final findings

Sample number: 1, 2, 3
Sample type: Sugar, 2%



Category	Score	Visualisation
1. Moment of first damage	C1 = 8/8	
2. Level of damage	8/8	
3. Level of material loss	8/8	
4. Weight difference	100% = 8/8	
5. Texture change	4/4	
6. Shape retention	4/4	
7. Level of cracking	4/4	
8. Structural integrity	4/4	
Total	48/48	

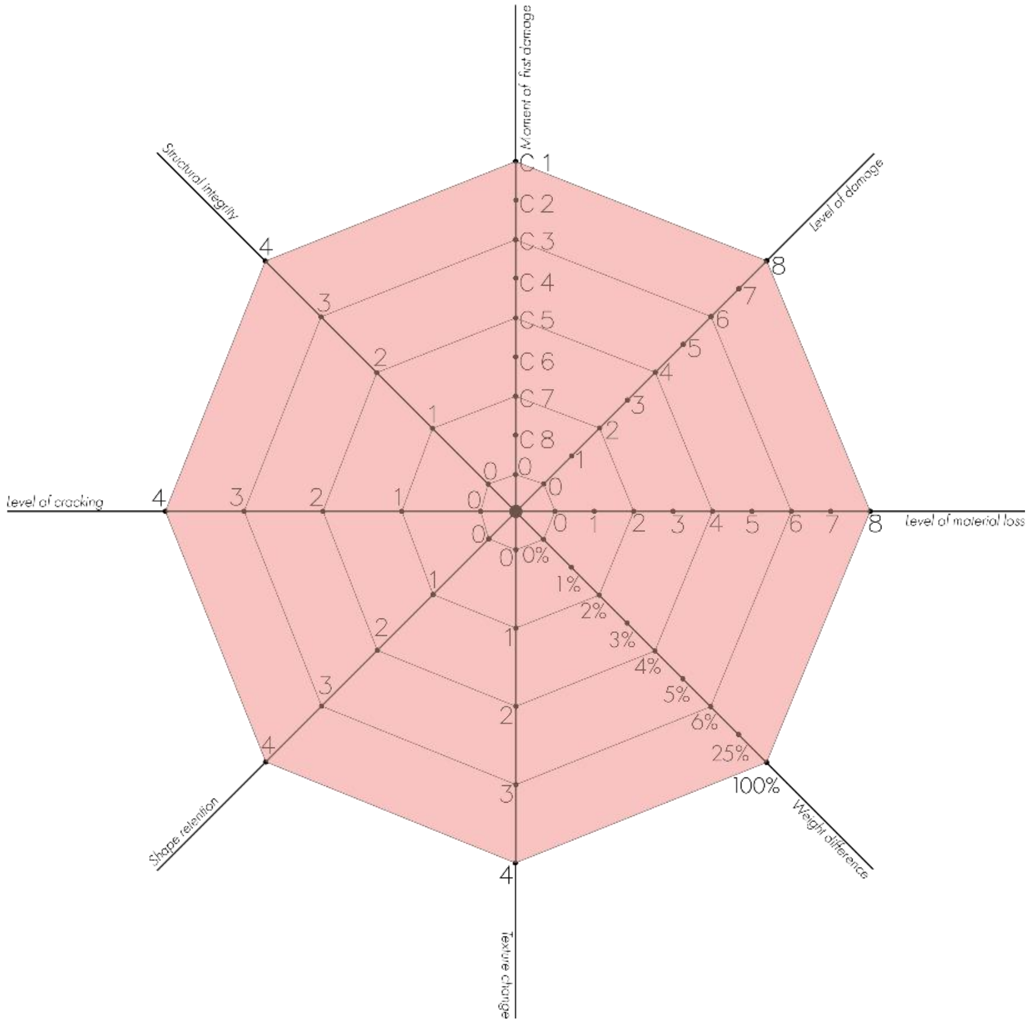
Interpretation sugar 5%, sample 1



Final findings: Sugar 5%, sample 1

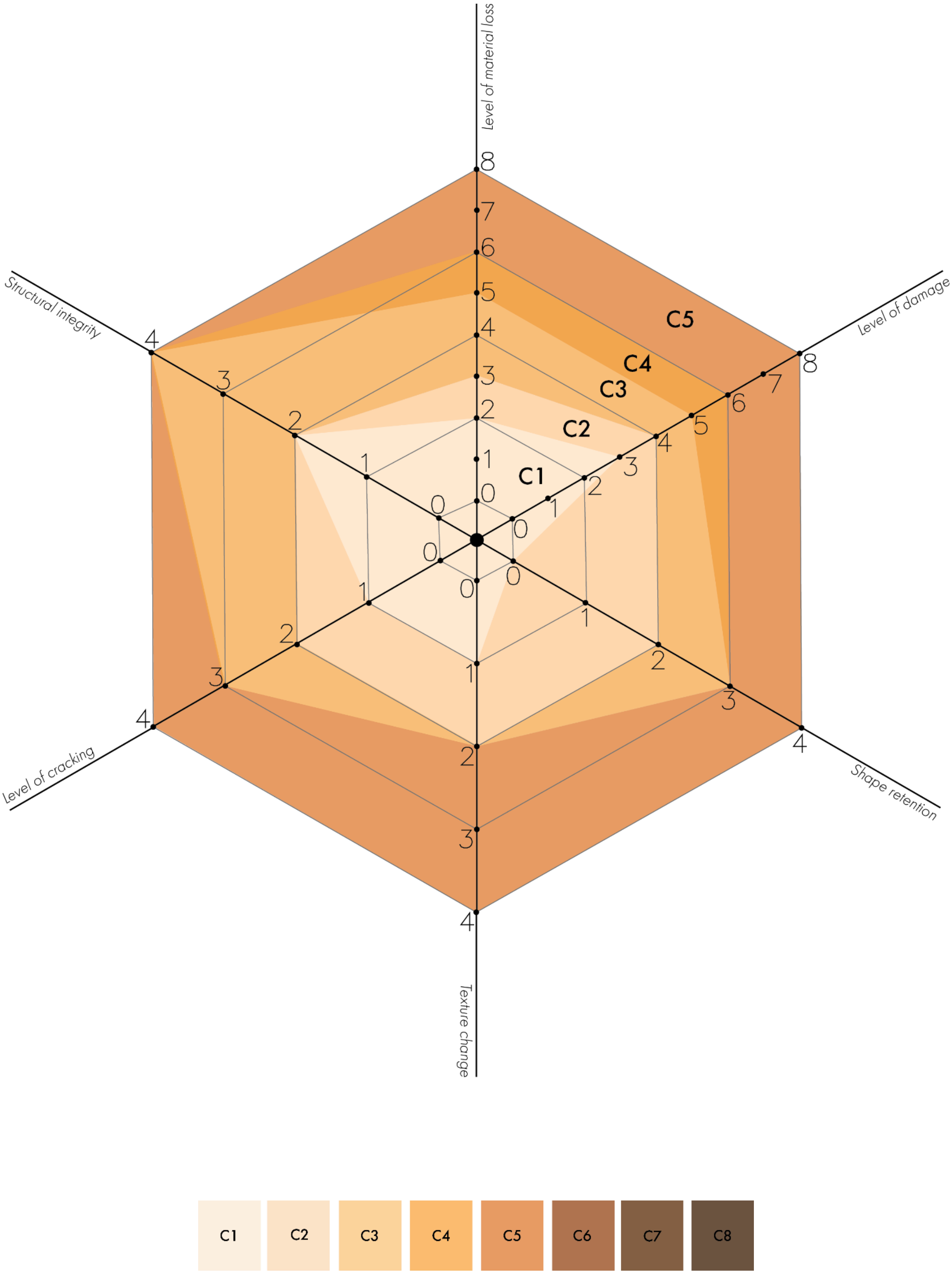
Final findings

Sample number: 1, 2, 3
Sample type: Sugar, 5%



Category	Score	Visualisation
1. Moment of first damage	C1 = 8/8	
2. Level of damage	8/8	
3. Level of material loss	8/8	
4. Weight difference	100% = 8/8	
5. Texture change	4/4	
6. Shape retention	4/4	
7. Level of cracking	4/4	
8. Structural integrity	4/4	
Total	48/48	

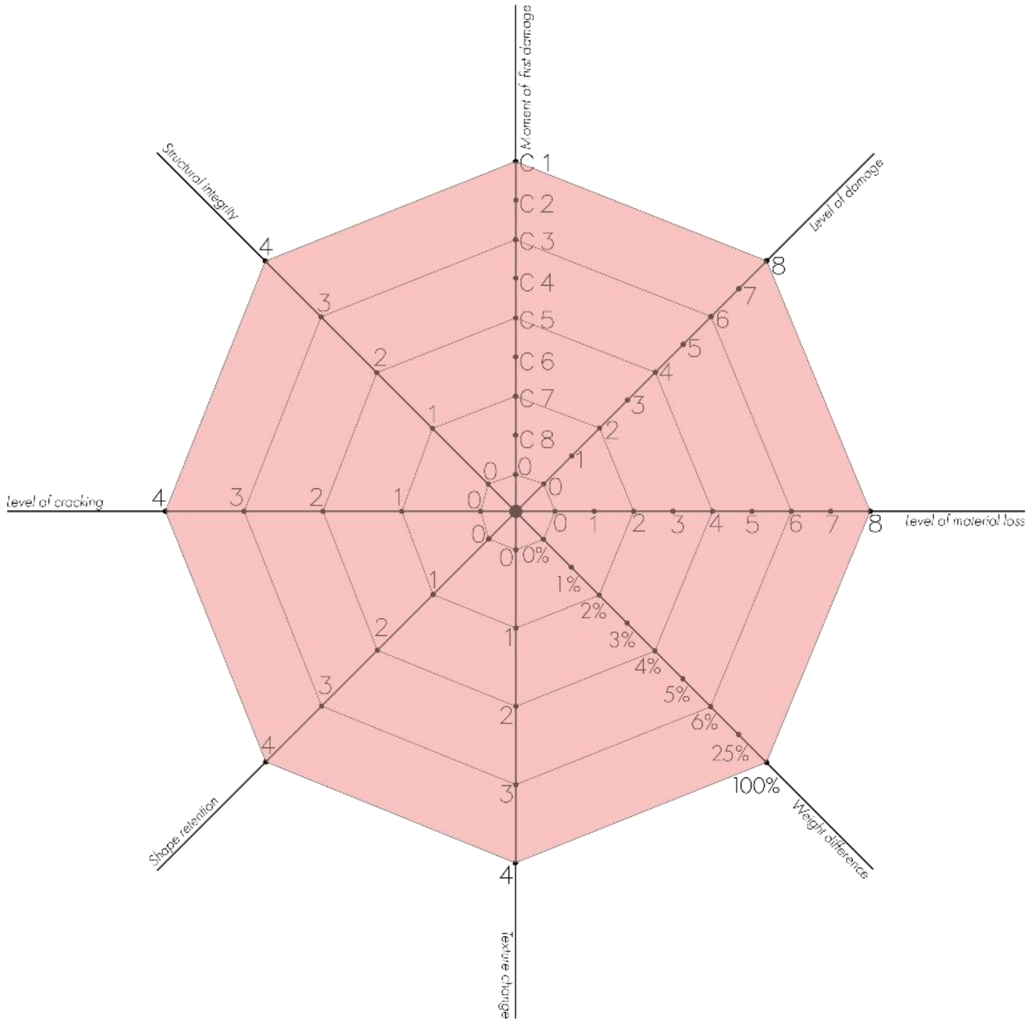
Interpretation sugar 5%, sample 2



Final findings: Sugar 5%, sample 2

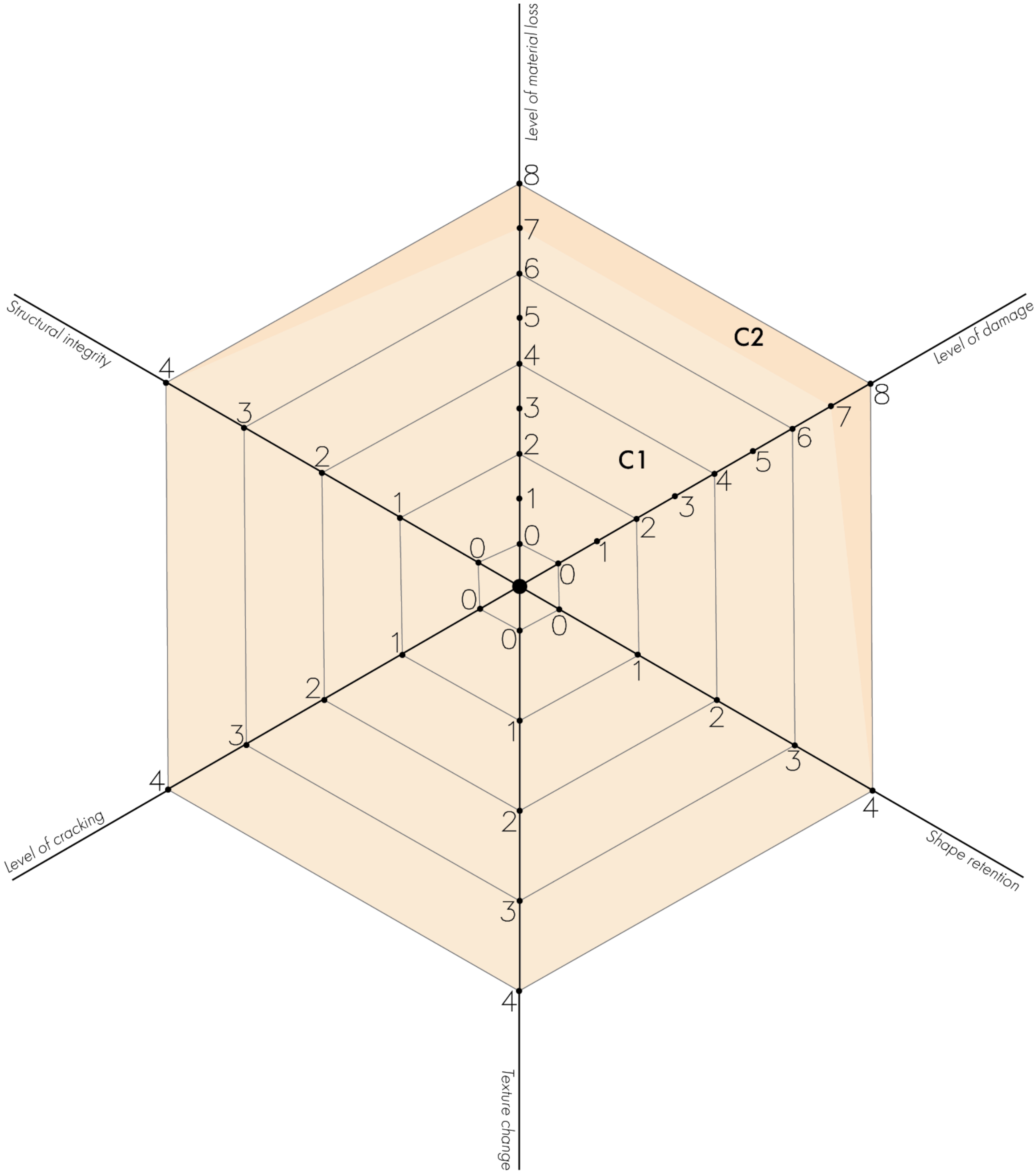
Final findings

Sample number: 1, 2, 3
Sample type: Sugar, 5%



Category	Score	Visualisation
1. Moment of first damage	C1 = 8/8	
2. Level of damage	8/8	
3. Level of material loss	8/8	
4. Weight difference	100% = 8/8	
5. Texture change	4/4	
6. Shape retention	4/4	
7. Level of cracking	4/4	
8. Structural integrity	4/4	
Total	48/48	

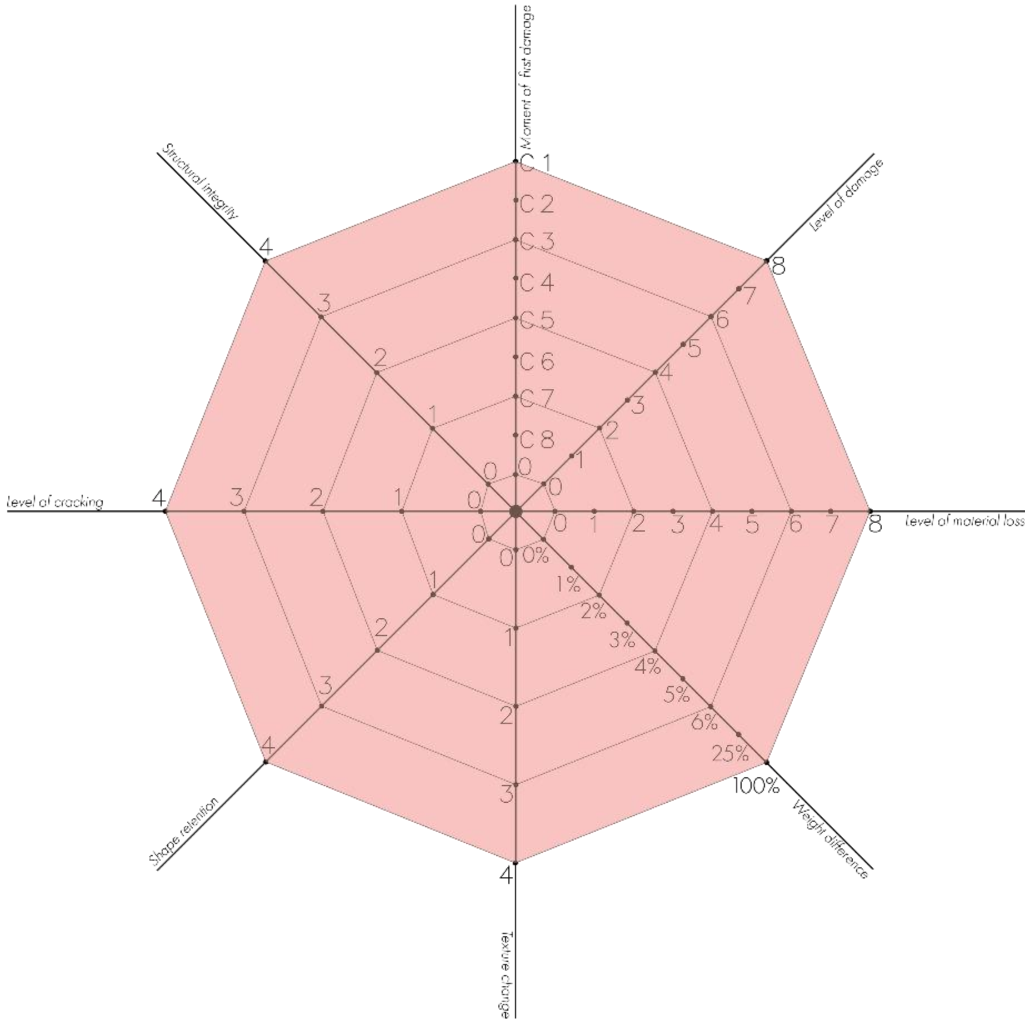
Interpretation sugar 5%, sample 3



Final findings: Sugar 5%, sample 3

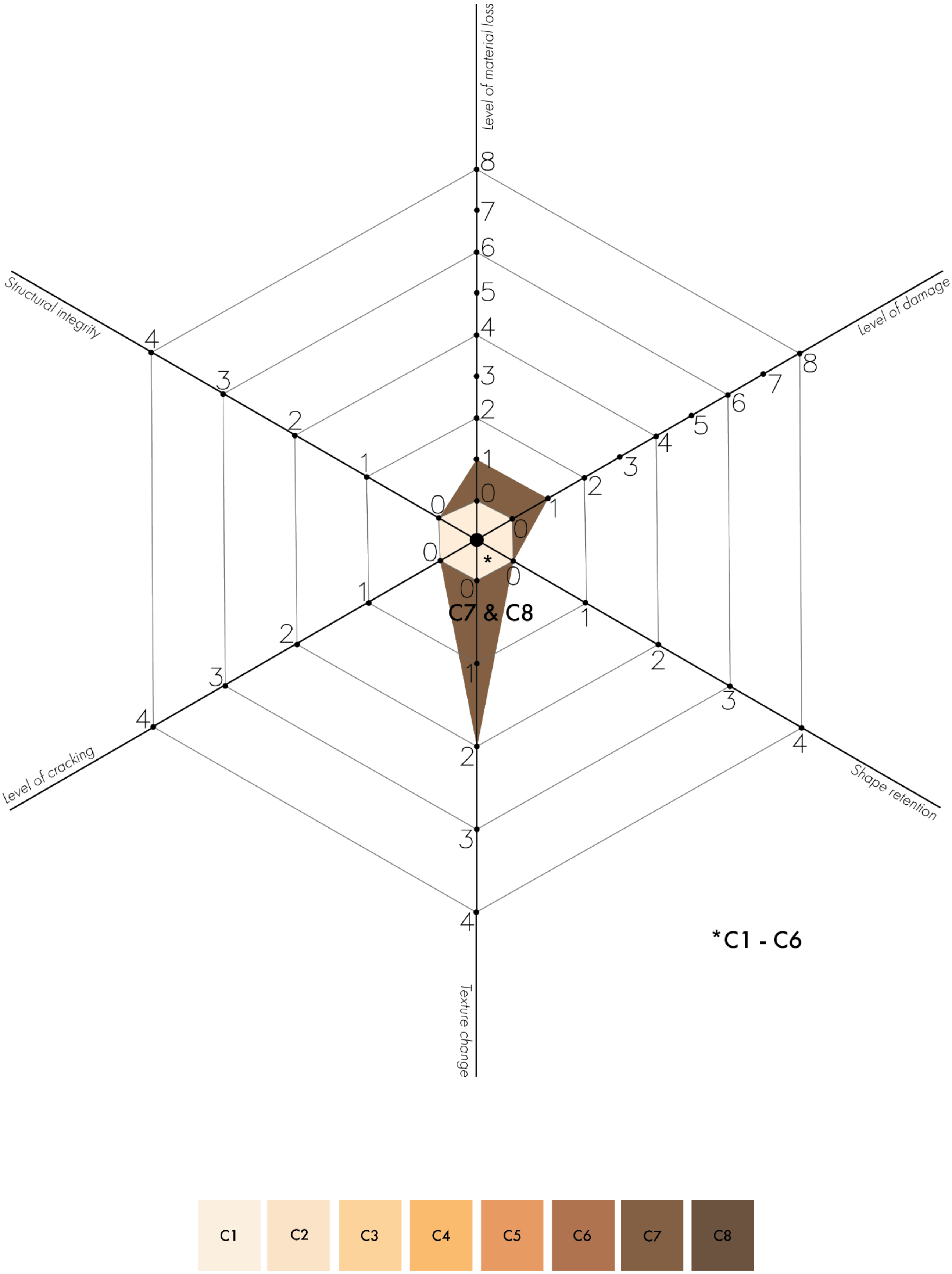
Final findings

Sample number: 1, 2, 3
Sample type: Sugar, 5%



Category	Score	Visualisation
1. Moment of first damage	C1 = 8/8	
2. Level of damage	8/8	
3. Level of material loss	8/8	
4. Weight difference	100% = 8/8	
5. Texture change	4/4	
6. Shape retention	4/4	
7. Level of cracking	4/4	
8. Structural integrity	4/4	
Total	48/48	

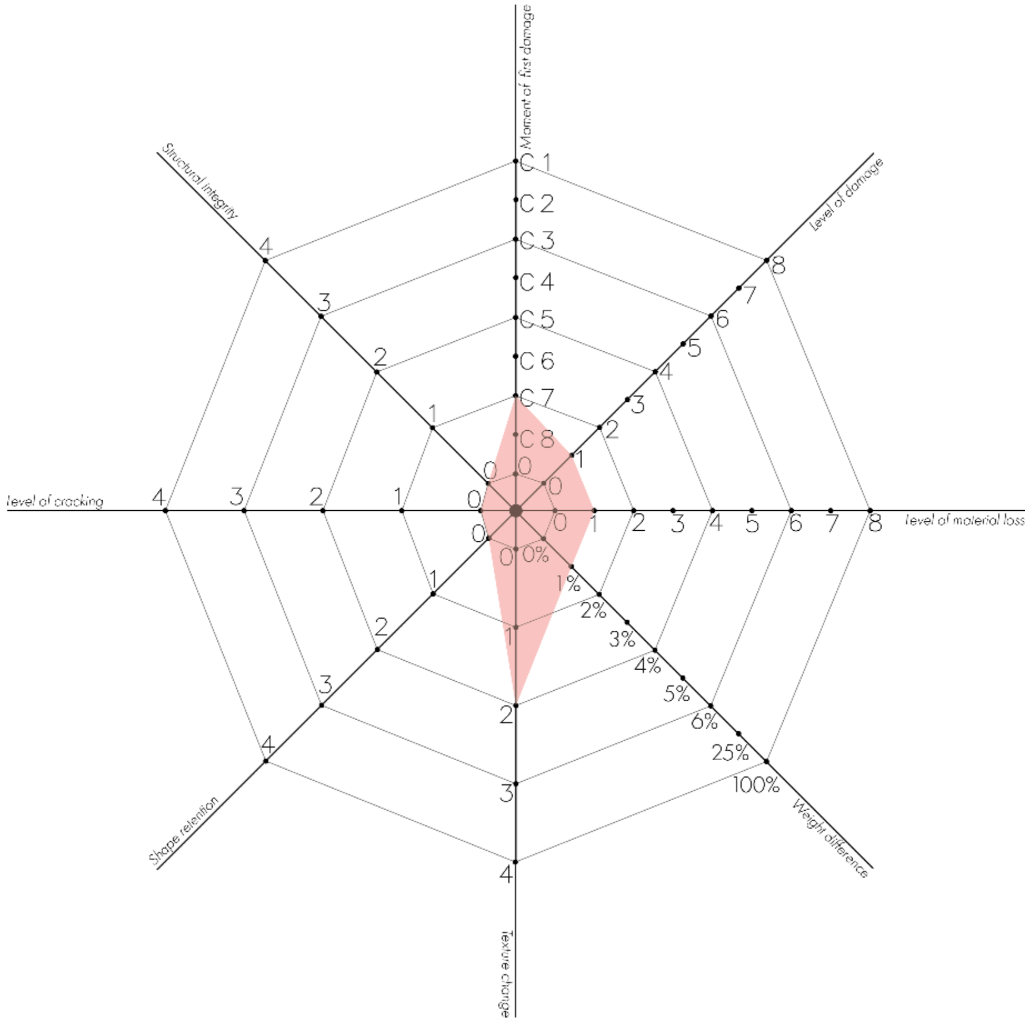
Interpretation cement, sample 1

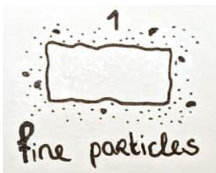
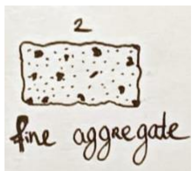
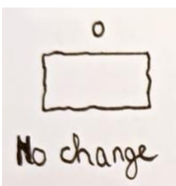
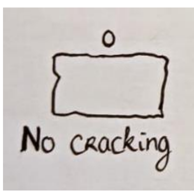
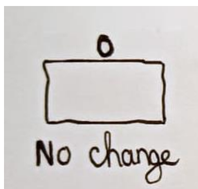


Final findings: Cement, sample 1

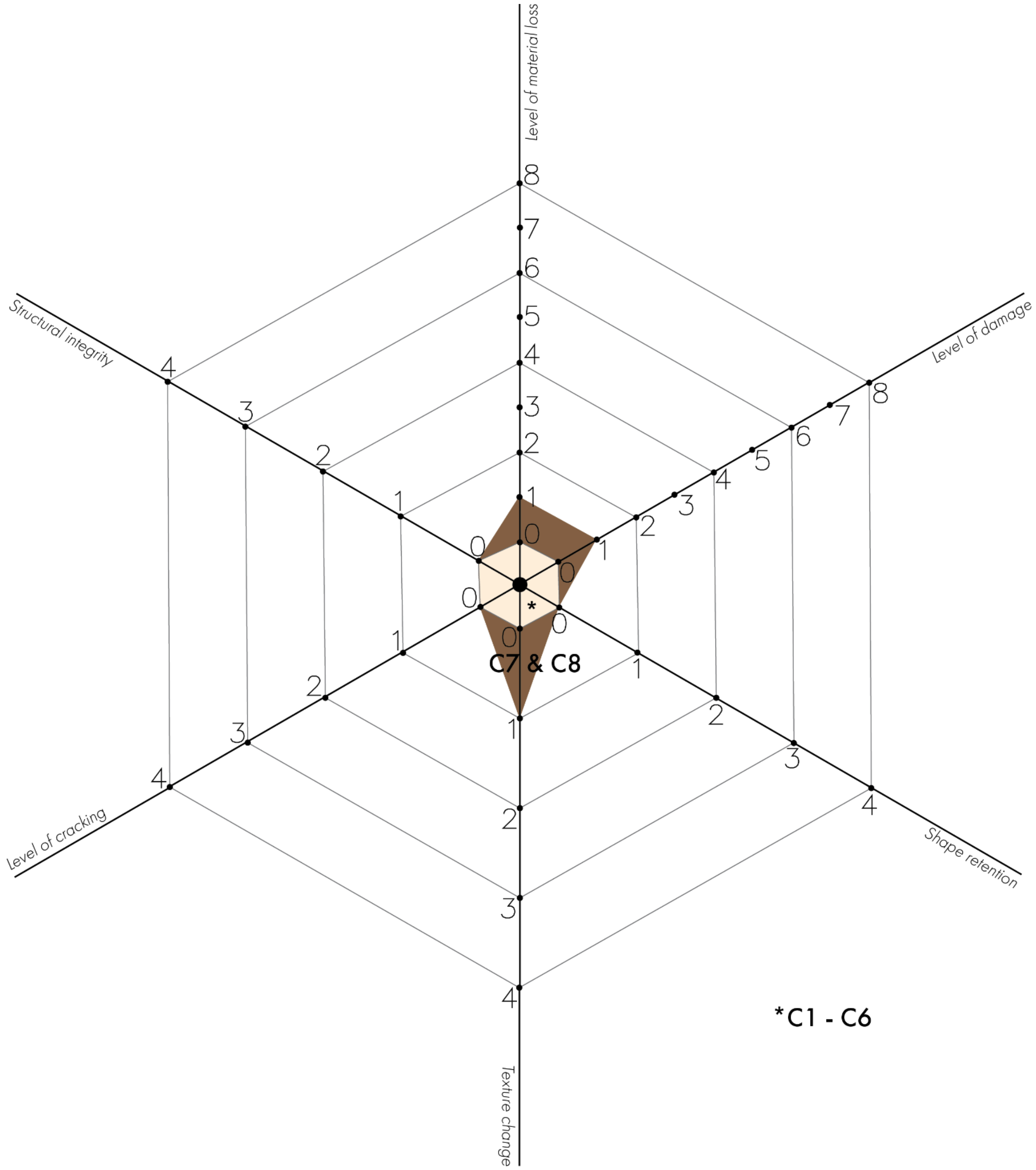
Final findings

Sample number: 1
Sample type: Cement



Category	Score	Visualisation
1. Moment of first damage	C7 = 2/8	
2. Level of damage	1/8	2.  3.  5. 
3. Level of material loss	1/8	
4. Weight difference	0.9% = 1/8	
5. Texture change	2/4	
6. Shape retention	0/4	6.  7.  8. 
7. Level of cracking	0/4	
8. Structural integrity	0/4	
Total	7/48	

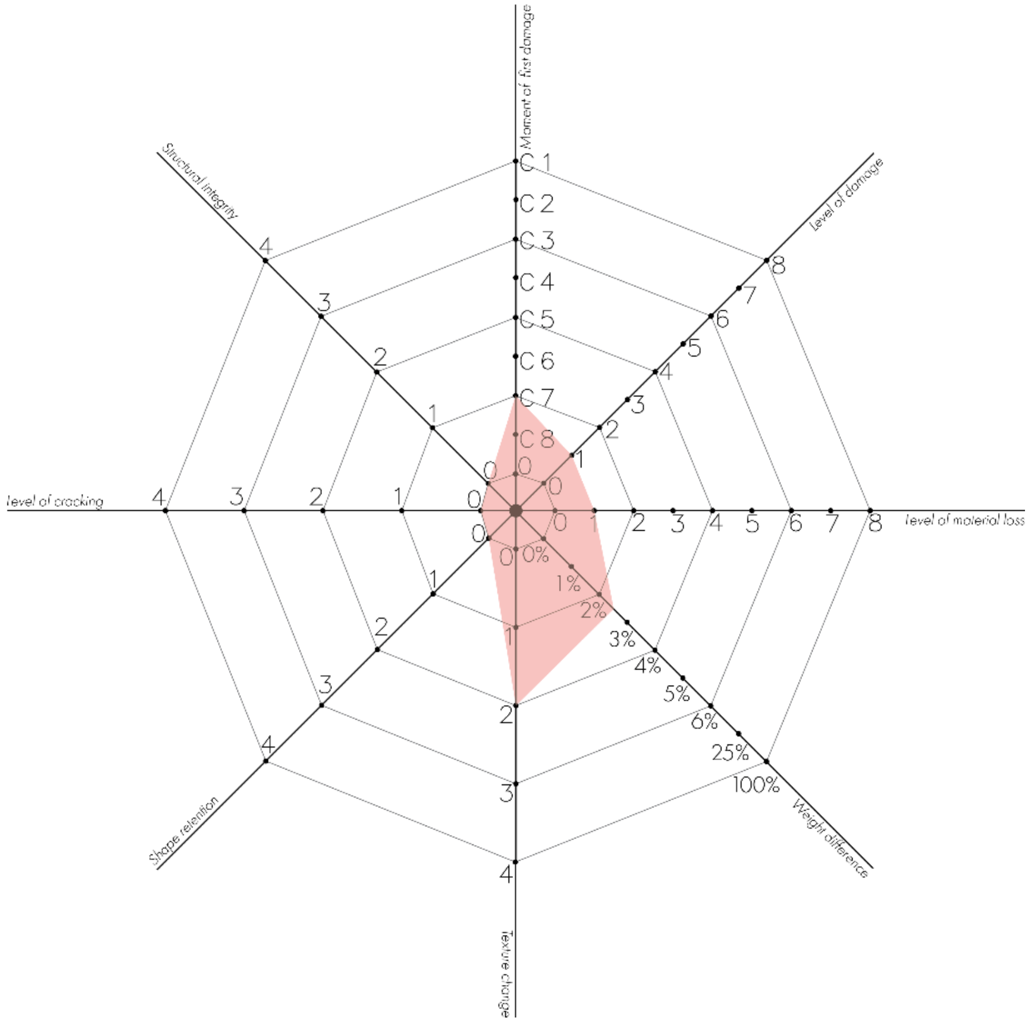
Interpretation cement, sample 2

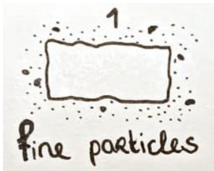
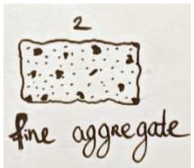
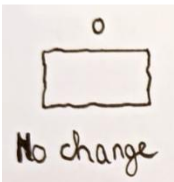
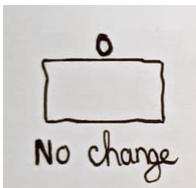


Final findings: Cement, sample 2

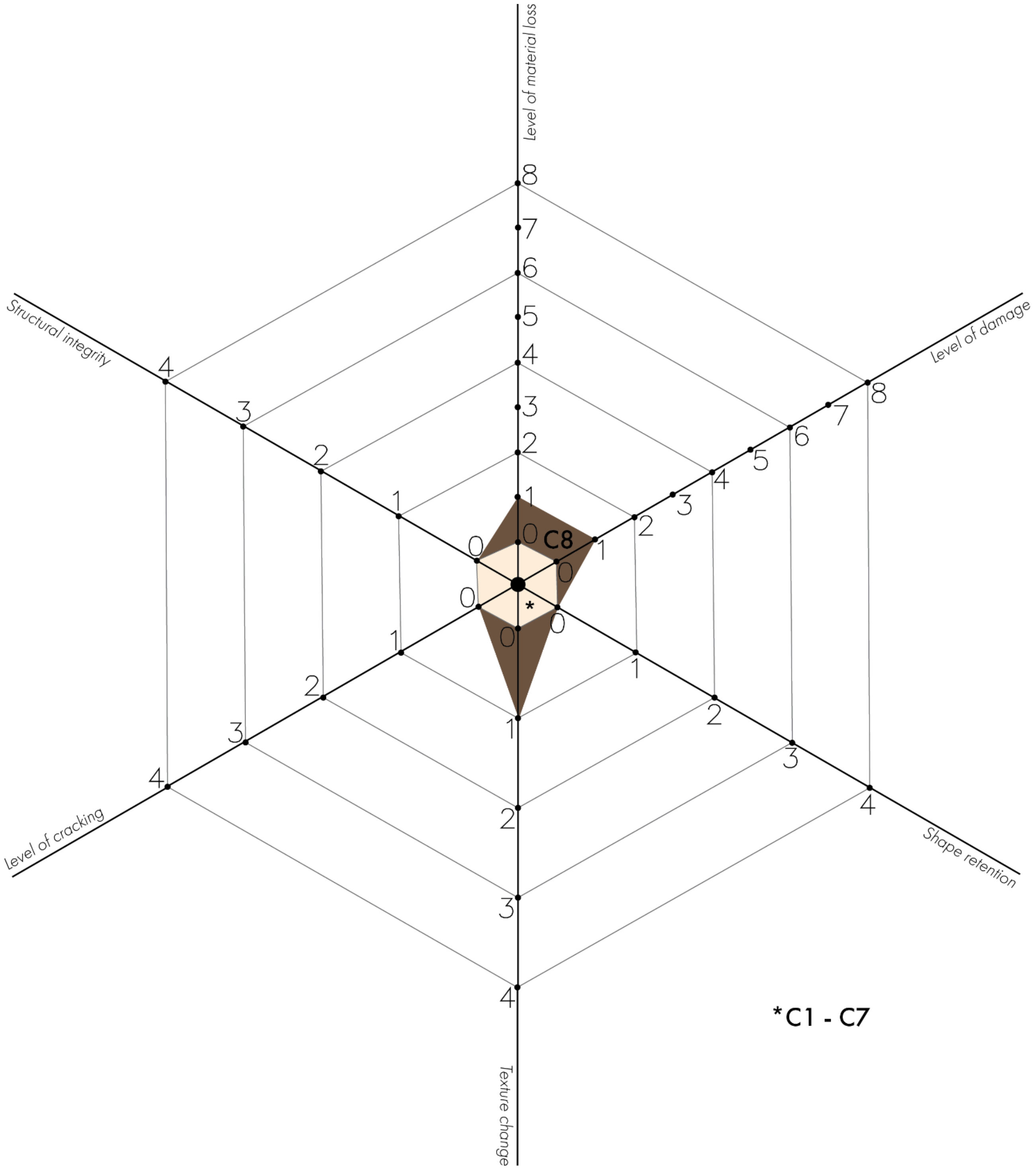
Final findings

Sample number: 2
Sample type: Cement



<table>
<tr><th>Category</th><th>Score</th><th>Visualisation</th></tr>
<tr><td>1. Moment of first damage</td><td>C7 = 2/8</td><td rowspan="9">2. 
3. 
5. 
6. 
7. 
8. </td></tr>
<tr><td>2. Level of damage</td><td>1/8</td></tr>
<tr><td>3. Level of material loss</td><td>1/8</td></tr>
<tr><td>4. Weight difference</td><td>2.5% = 2.5/8</td></tr>
<tr><td>5. Texture change</td><td>2/4</td></tr>
<tr><td>6. Shape retention</td><td>0/4</td></tr>
<tr><td>7. Level of cracking</td><td>0/4</td></tr>
<tr><td>8. Structural integrity</td><td>0/4</td></tr>
<tr><td>Total</td><td>8.5/48</td></tr>
</table>

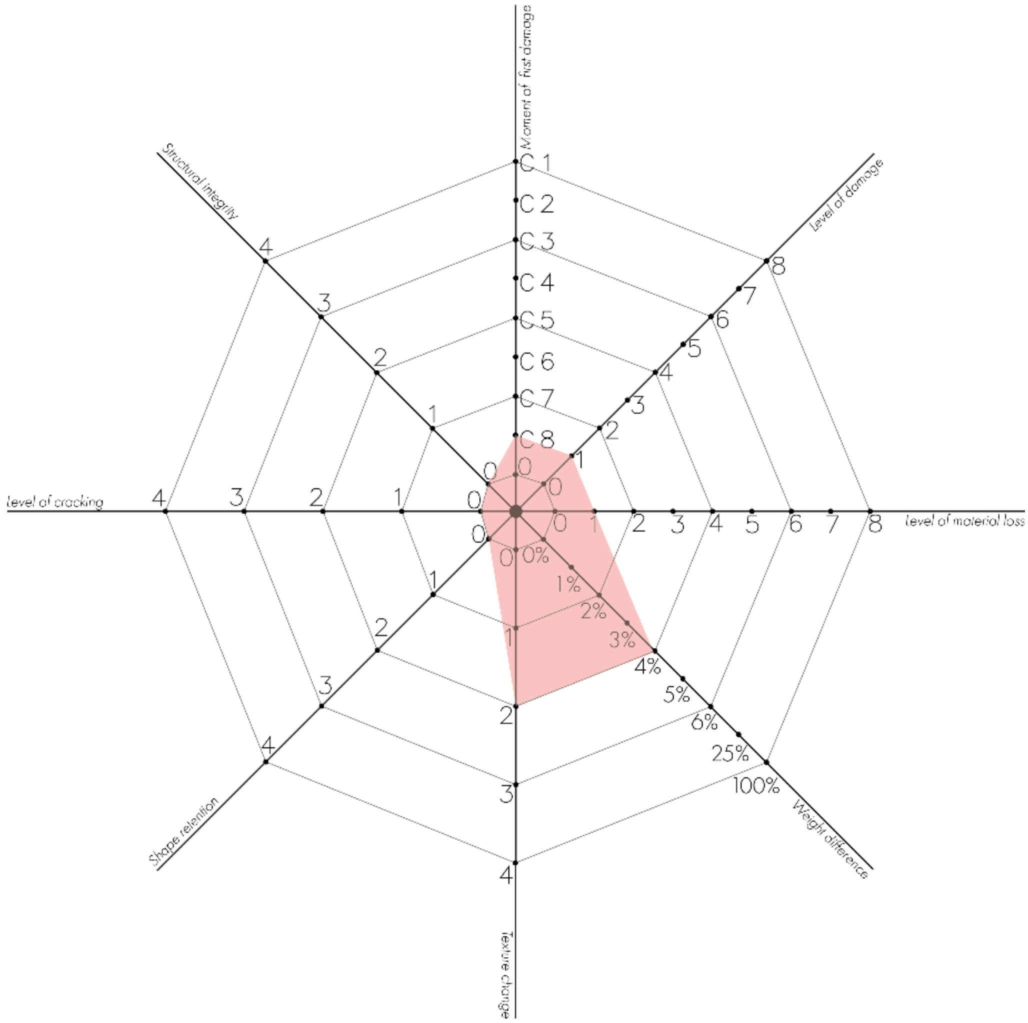
Interpretation cement, sample 3



Final findings: Cement, sample 3

Final findings

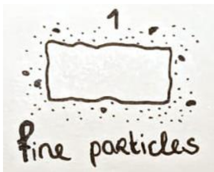
Sample number: 3
Sample type: Cement



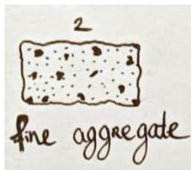
<table>
<tr><th>Category</th><th>Score</th><th>Visualisation</th></tr>
<tr><td>1. Moment of first damage</td><td>C8 = 1/8</td><td rowspan="9">

2.

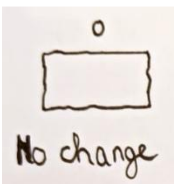
3.



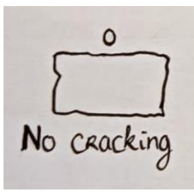
5.



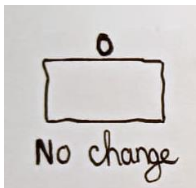
6.



7.

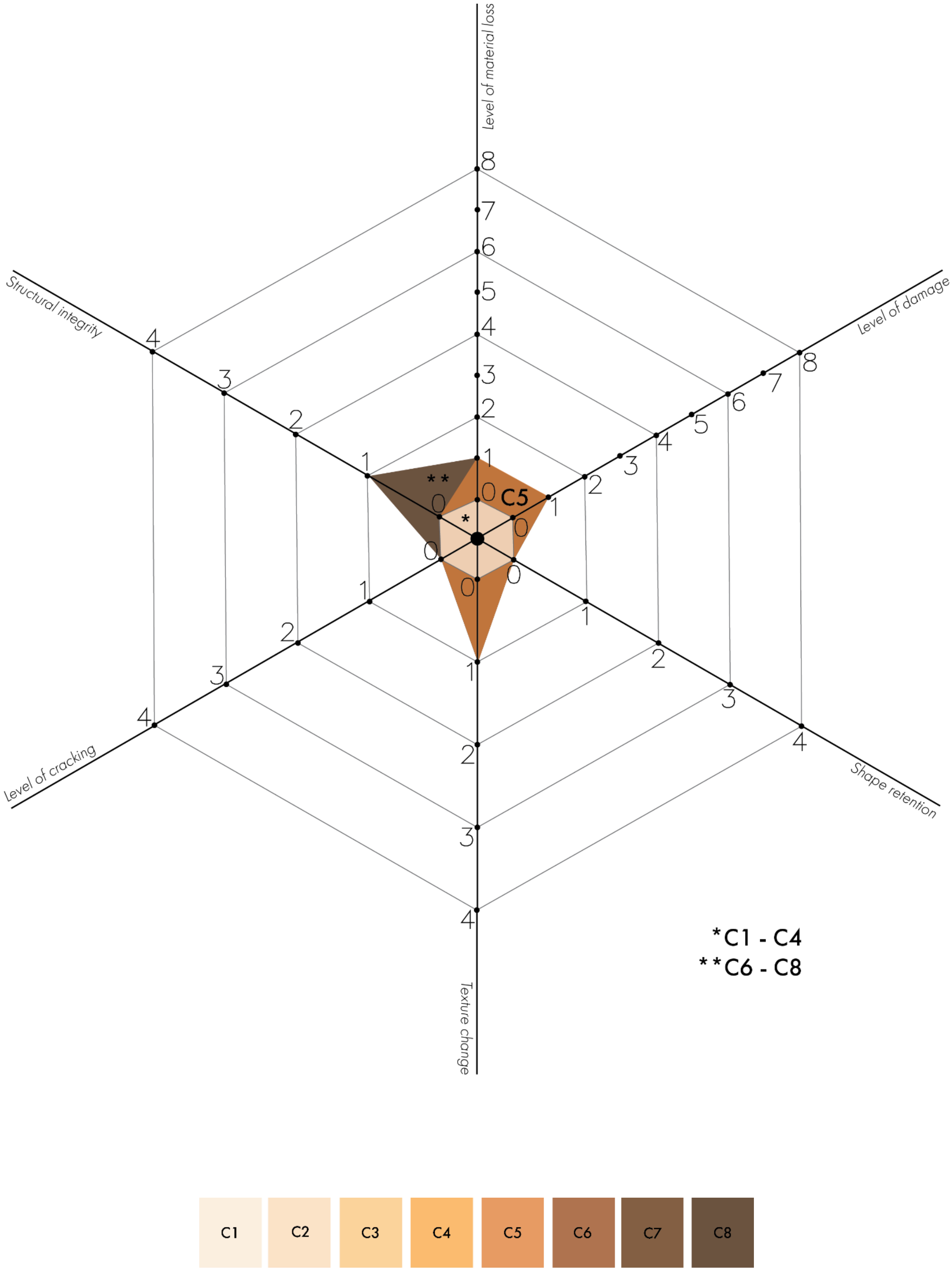


8.



</td></tr>
<tr><td>2. Level of damage</td><td>1/8</td></tr>
<tr><td>3. Level of material loss</td><td>1/8</td></tr>
<tr><td>4. Weight difference</td><td>3.9% = 4/8</td></tr>
<tr><td>5. Texture change</td><td>2/4</td></tr>
<tr><td>6. Shape retention</td><td>0/4</td></tr>
<tr><td>7. Level of cracking</td><td>0/4</td></tr>
<tr><td>8. Structural integrity</td><td>0/4</td></tr>
<tr><td>Total</td><td>9/48</td></tr>
</table>

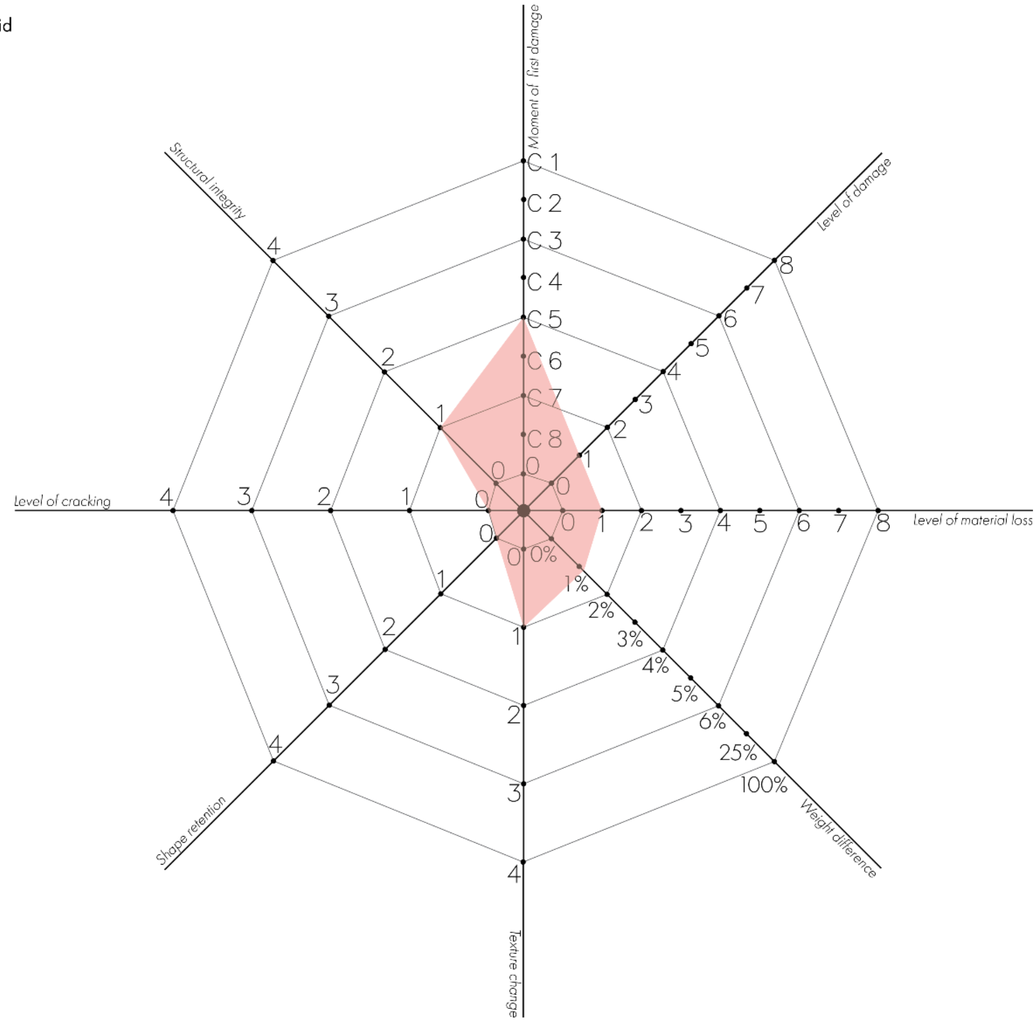
Interpretation albumen solid, sample 1

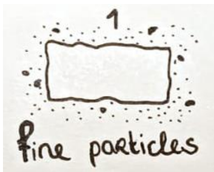
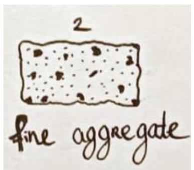
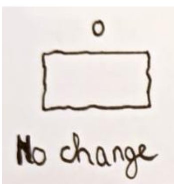
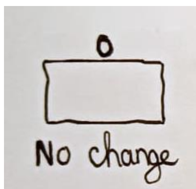


Final findings: Albumen solid, sample 1

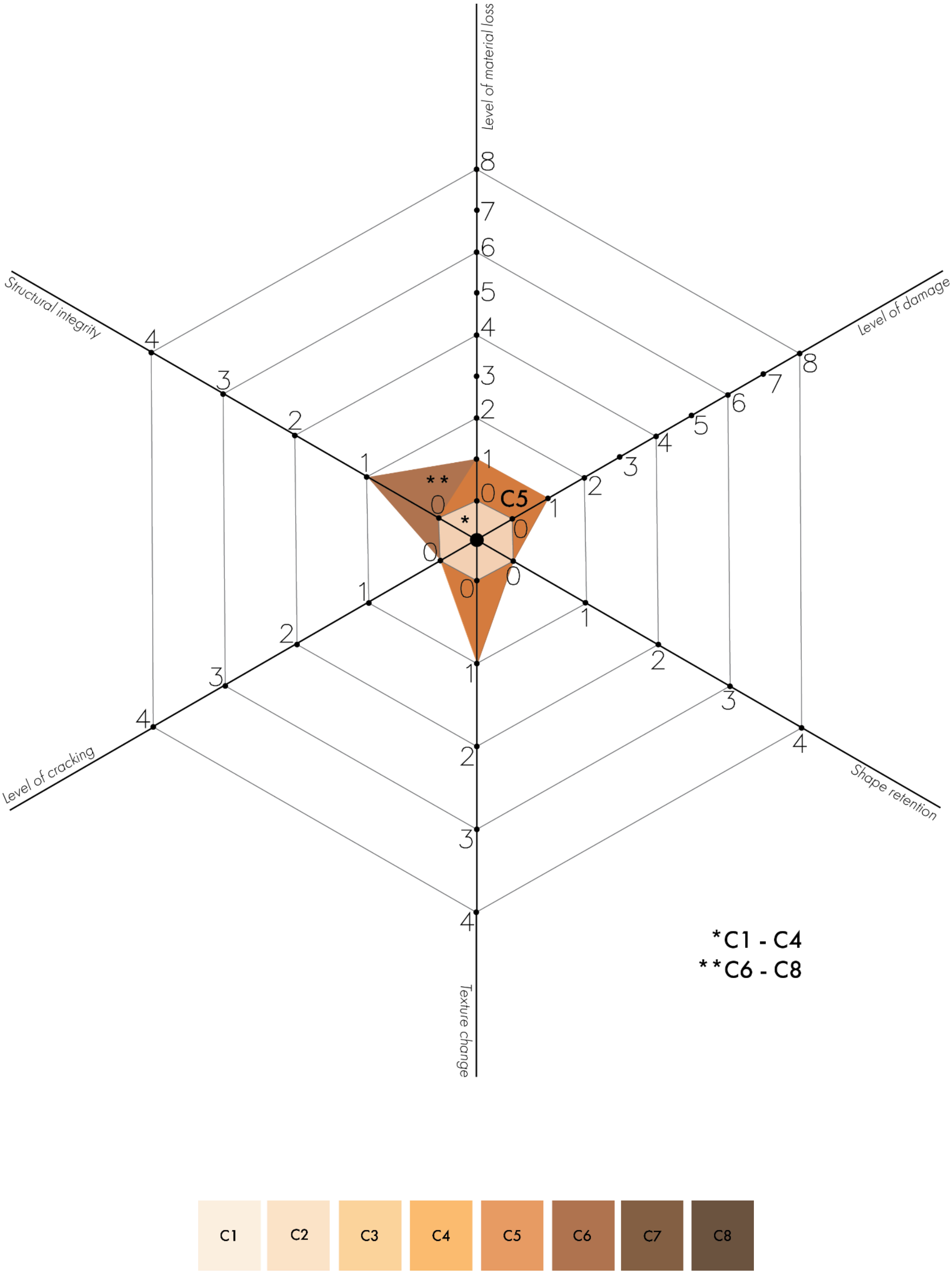
Final findings

Sample number: 1
Sample type: Albumen, solid



Category	Score	Visualisation
1. Moment of first damage	C7 = 2/8	**2.**  **3.**  **5.**  **6.**  **7.**  **8.** 
2. Level of damage	1/8	
3. Level of material loss	1/8	
4. Weight difference	1.2% = 1/8	
5. Texture change	2/4	
6. Shape retention	0/4	
7. Level of cracking	0/4	
8. Structural integrity	0/4	
Total	7/48	

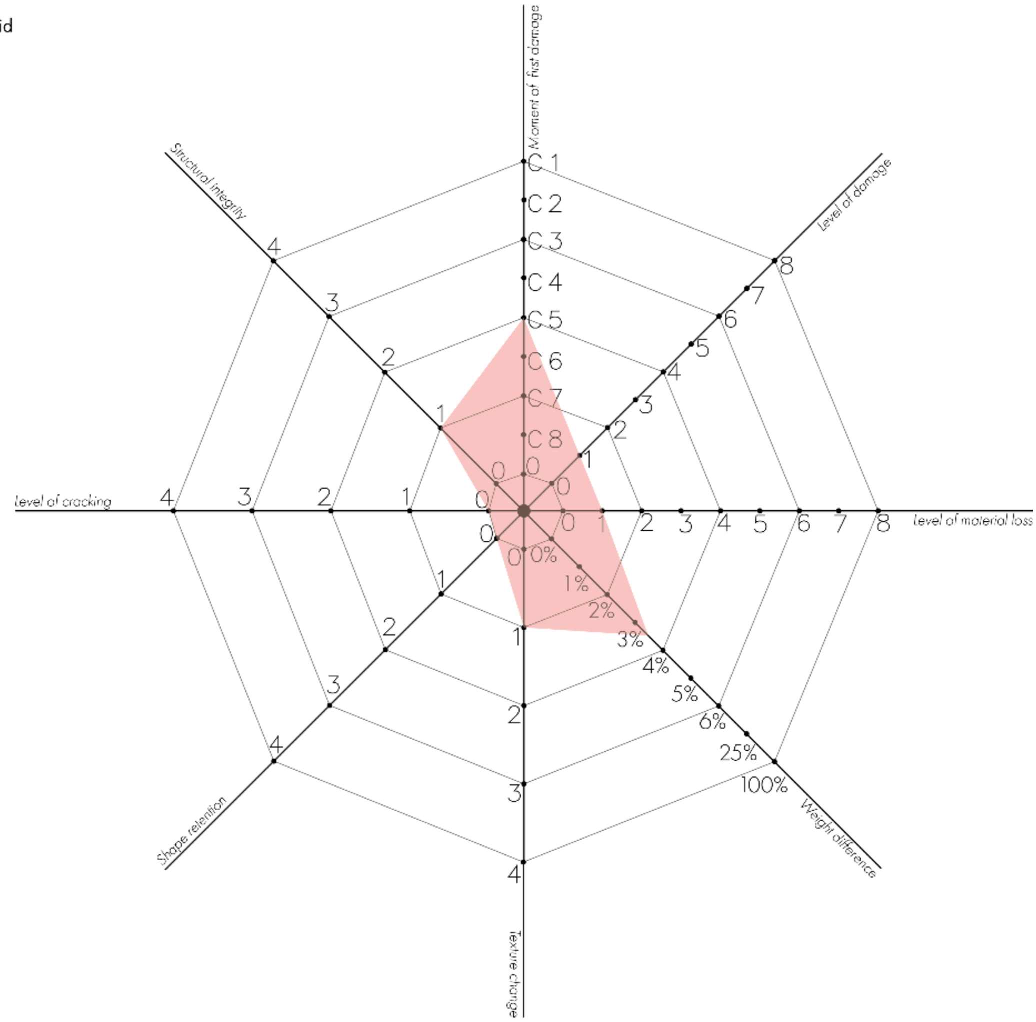
Interpretation albumen solid, sample 2



Final findings: Albumen solid, sample 2

Final findings

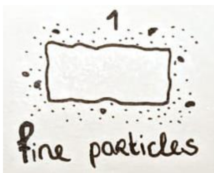
Sample number: 2
Sample type: Albumen, solid



Category	Score	Visualisation
1. Moment of first damage	C5 = 4/8	
2. Level of damage	1/8	
3. Level of material loss	1/8	
4. Weight difference	3.3% = 3.5/8	
5. Texture change	1/4	
6. Shape retention	0/4	
7. Level of cracking	0/4	
8. Structural integrity	1/4	
Total	11.5/48	

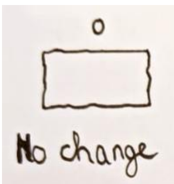
2.

3.



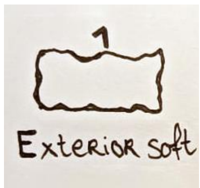
5.

6.

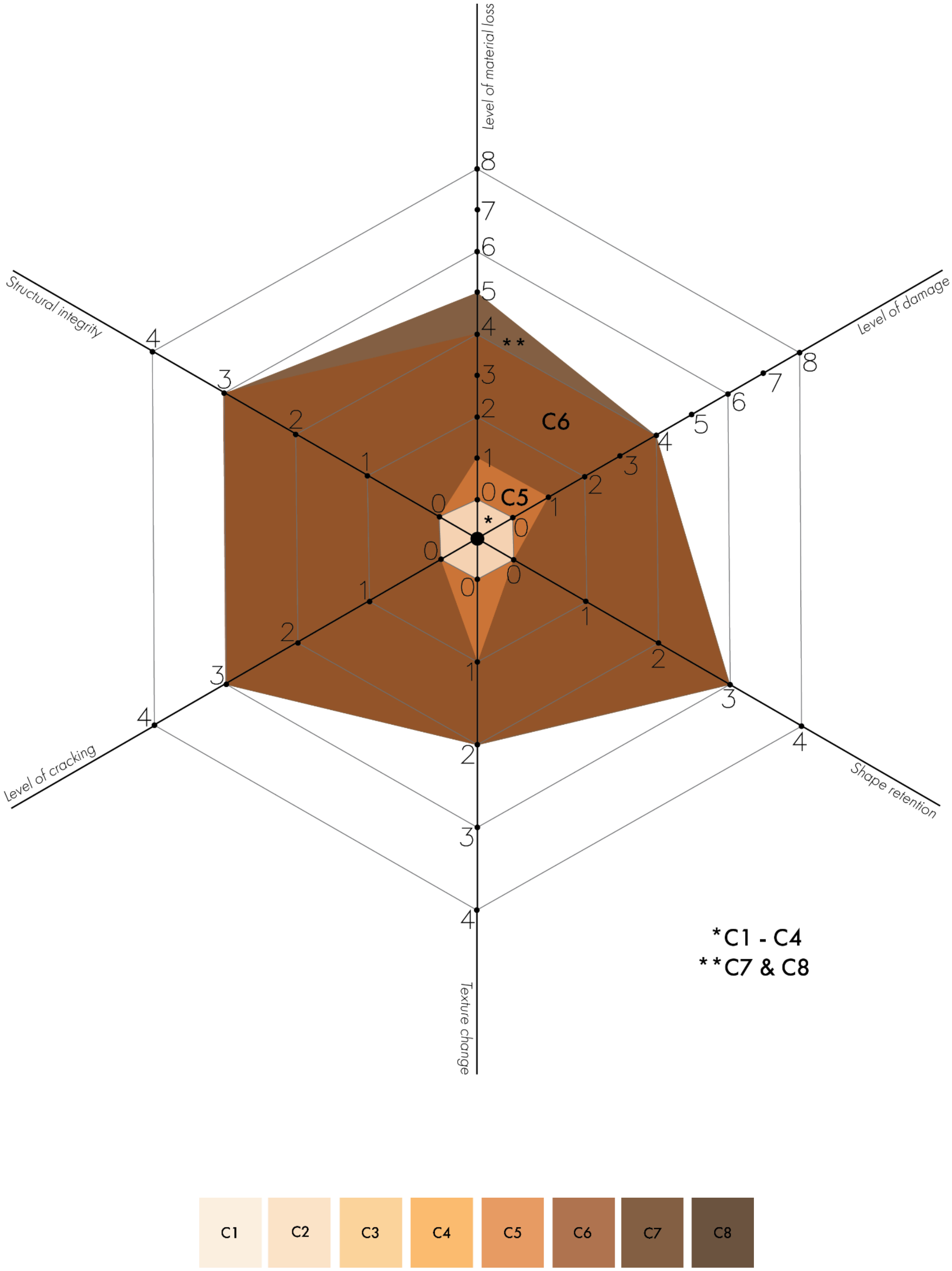


7.

8.



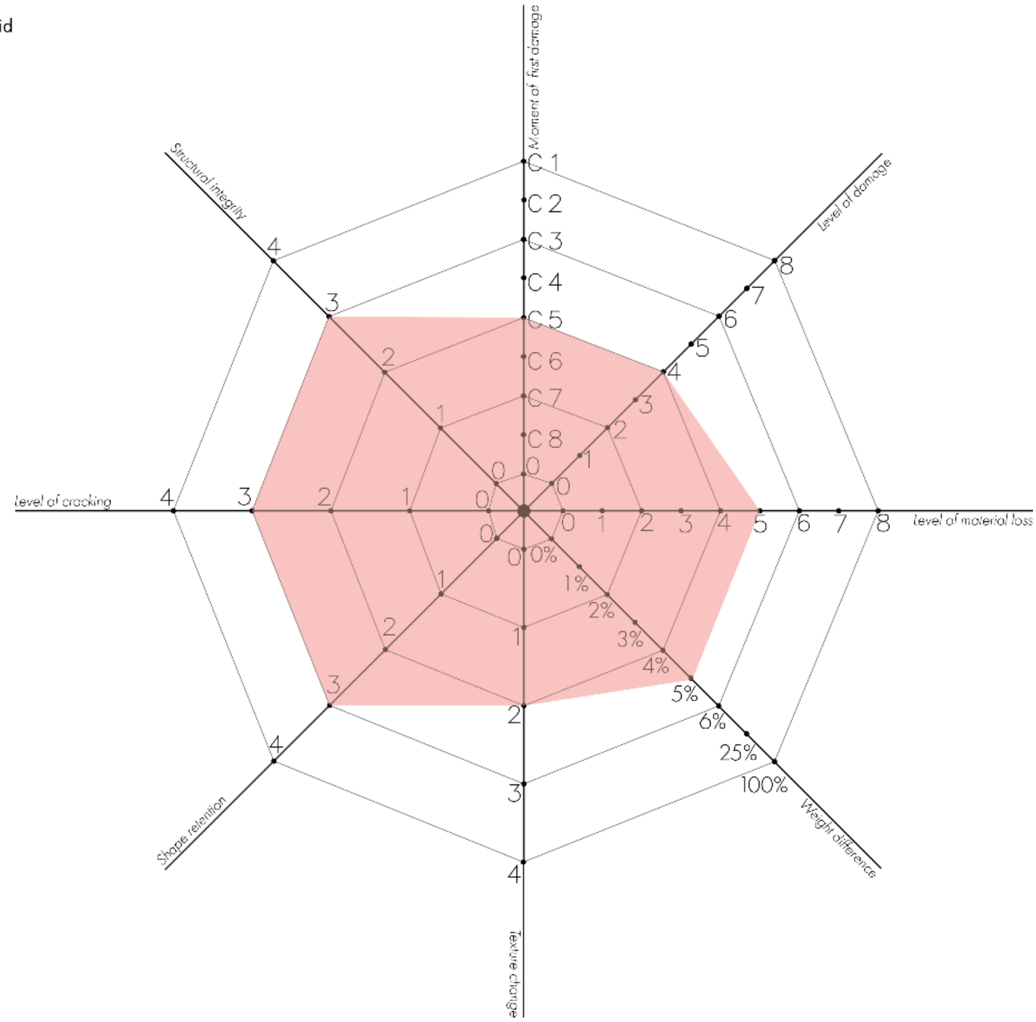
Interpretation albumen solid, sample 3



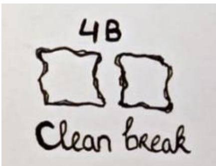
Final findings: Albumen solid, sample 3

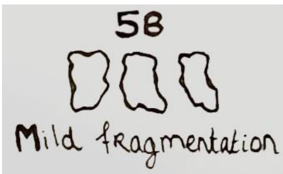
Final findings

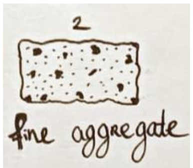
Sample number: 3
Sample type: Albumen, solid

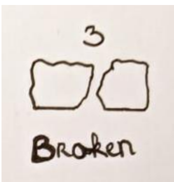


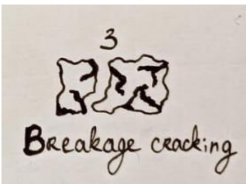
<table>
<tr><th>Category</th><th>Score</th><th>Visualisation</th></tr>
<tr><td>1. Moment of first damage</td><td>C5 = 4/8</td><td rowspan="9">

2. 

3. 

5. 

6. 

7. 

8. 

</td></tr>
<tr><td>2. Level of damage</td><td>4/8</td></tr>
<tr><td>3. Level of material loss</td><td>5/8</td></tr>
<tr><td>4. Weight difference</td><td>5% = 5/8</td></tr>
<tr><td>5. Texture change</td><td>2/4</td></tr>
<tr><td>6. Shape retention</td><td>3/4</td></tr>
<tr><td>7. Level of cracking</td><td>3/4</td></tr>
<tr><td>8. Structural integrity</td><td>3/4</td></tr>
<tr><td>Total</td><td>29/48</td></tr>
</table>

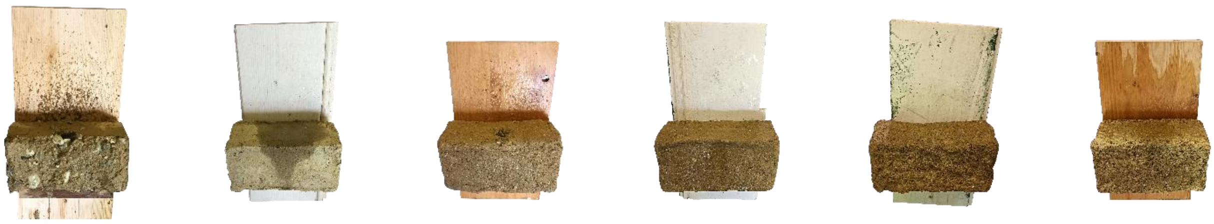
Appendix 15. Drip test – Images

Round 1

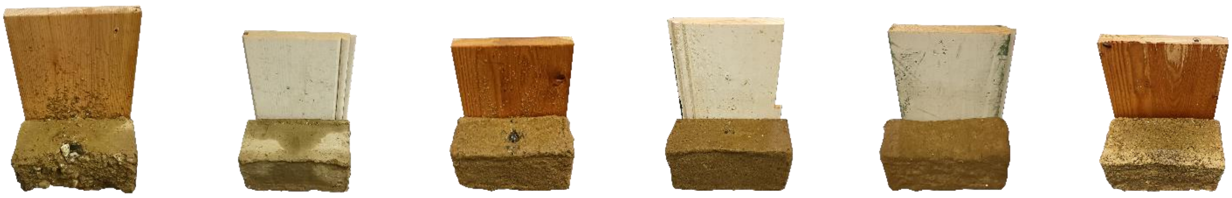
Regular – Cement – Sugar: 5% – Sugar: 2% – Albumen: Liquid – Albumen: Solid

R1 - 1 hour

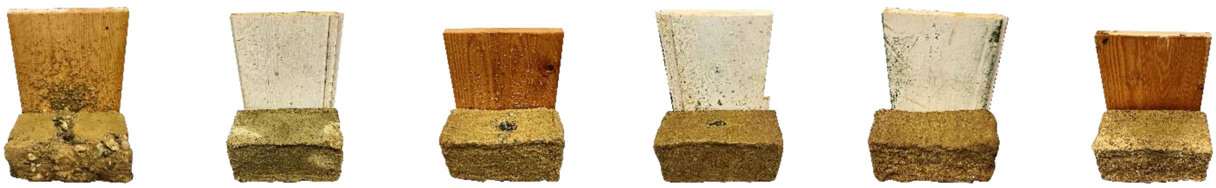
R1 - 2 hours



R1 - 3 hours



R1 - 4 hours



Round 1

Regular – Cement – Sugar: 5% – Sugar: 2% – Albumen: Liquid – Albumen: Solid

R1 - 5 hours

R1 - 6 hours

R1 - 8 hours

R1 - 24 hours

Round 2

Regular – Cement – Sugar: 5% – Sugar: 2% – Albumen: Liquid – Albumen: Solid

R2 - 1 hour

R2 - 2 hours

R2 - 3 hours

R2 - 4 hours

Round 2

Regular – Cement – Sugar: 5% – Sugar: 2% – Albumen: Liquid – Albumen: Solid

R2 - 5 hours

R2 - 6 hours

R2 - 8 hours

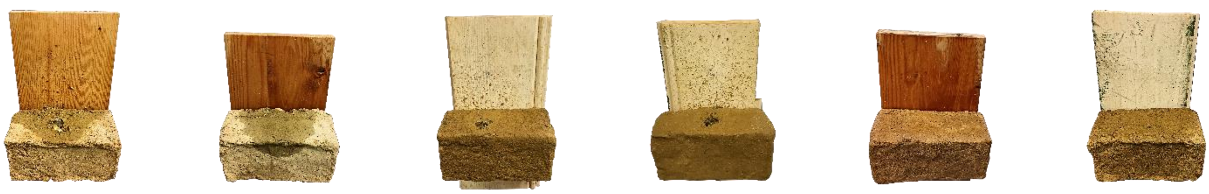
R2 - 24 hours

Round 3

Regular – Cement – Sugar: 5% – Sugar: 2% – Albumen: Liquid – Albumen: Solid

R3 - 1 hour

R3 - 2 hours



R3 - 3 hours

R3 - 4 hours

Round 3

Regular – Cement – Sugar: 5% – Sugar: 2% – Albumen: Liquid – Albumen: Solid

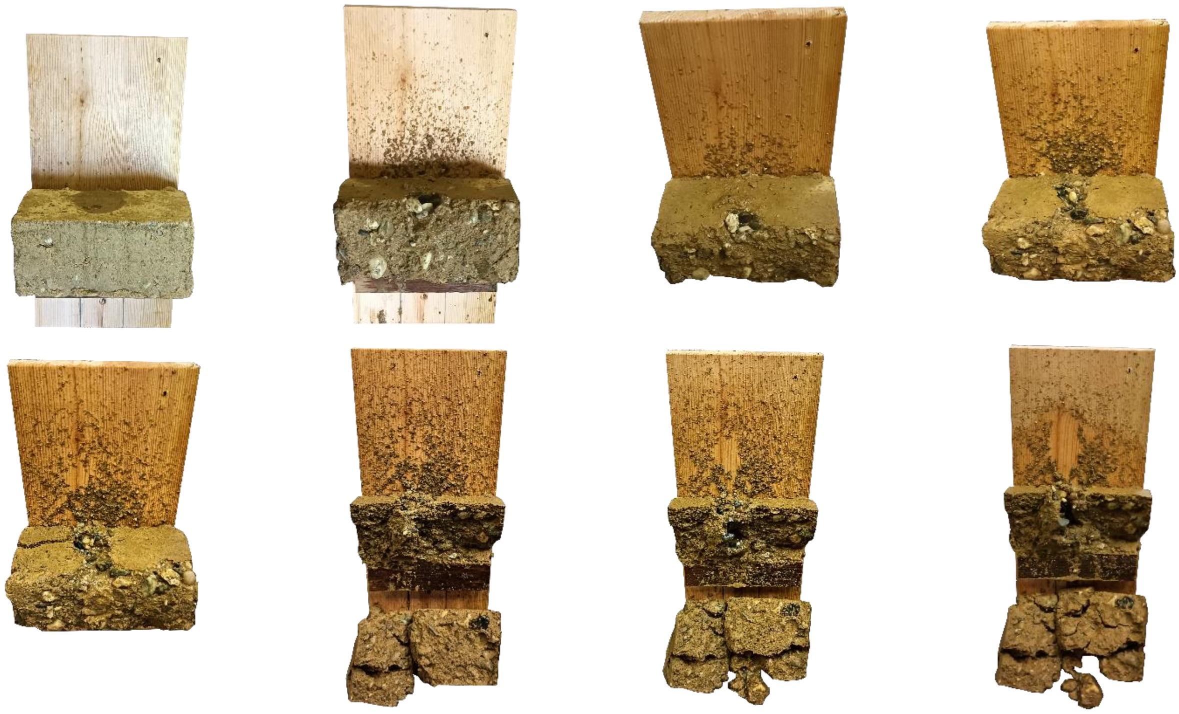
R3 - 5 hours

R3 - 6 hours

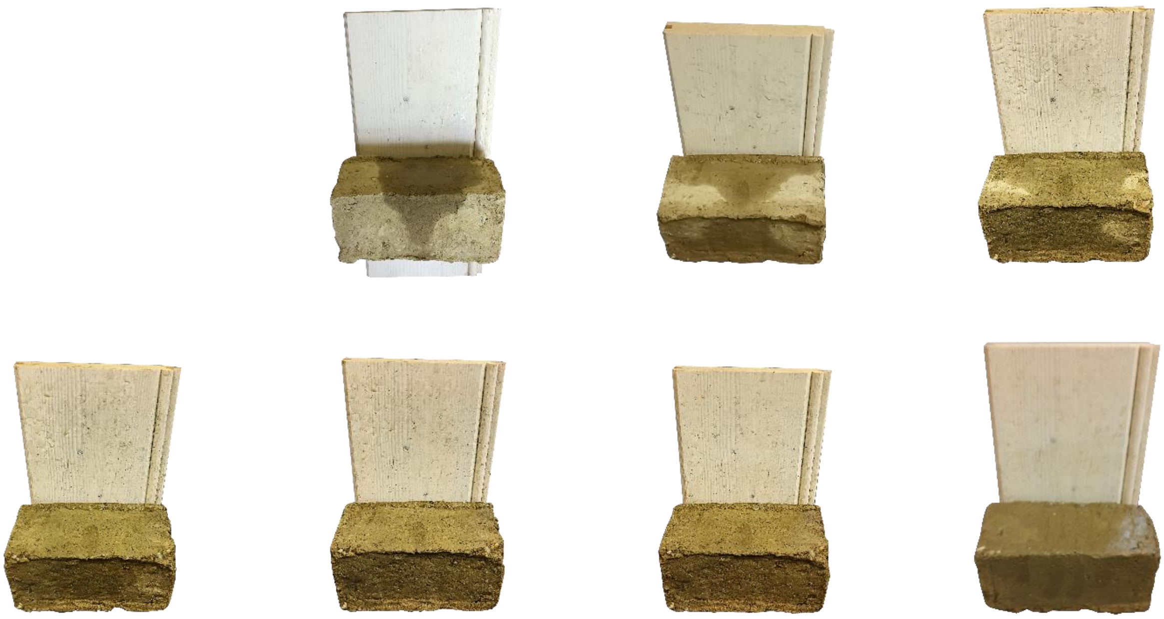
R3 - 8 hours

R3 - 24 hours

Round 1 - Regular

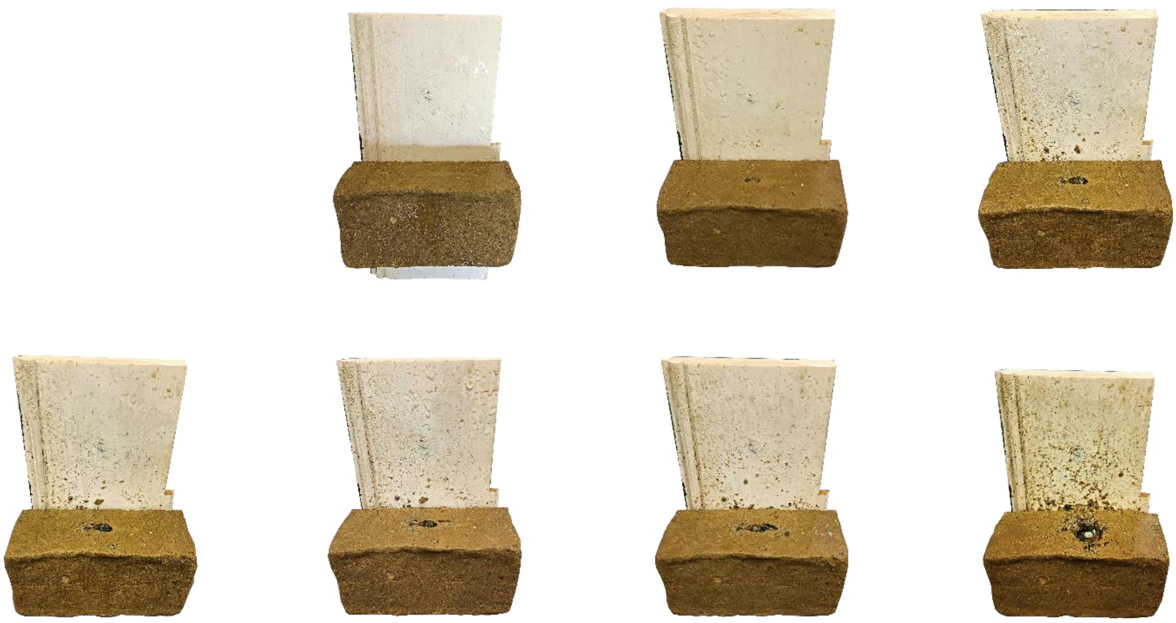


Round 1 - Cement

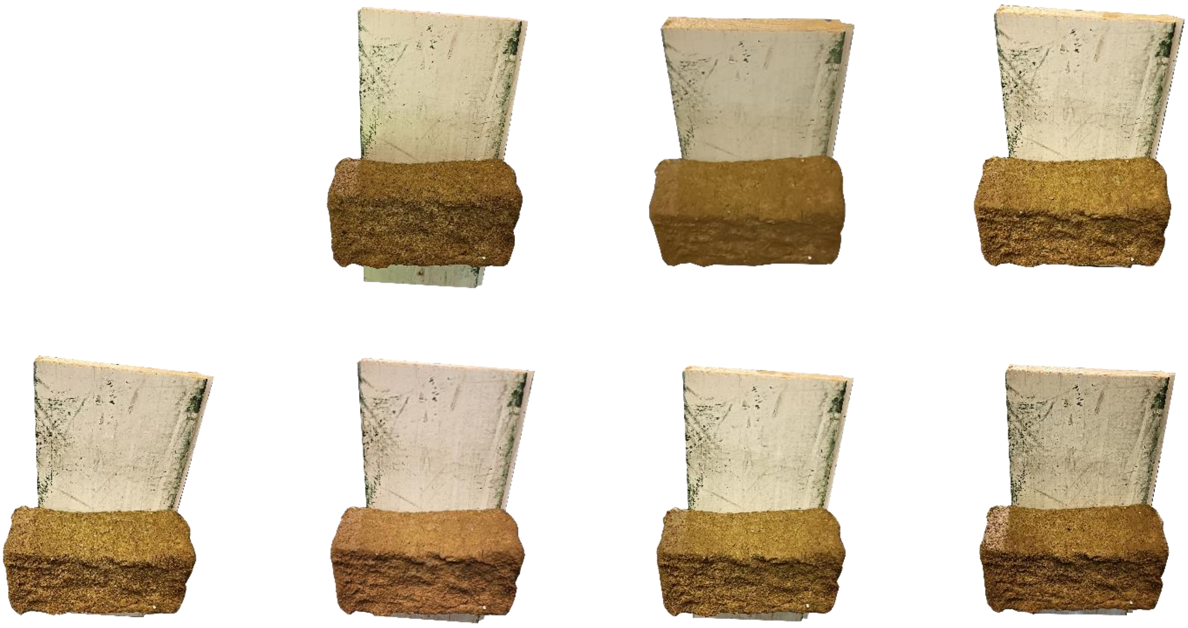


Round 1 - Sugar: 5%

Round 1 - Sugar: 2%



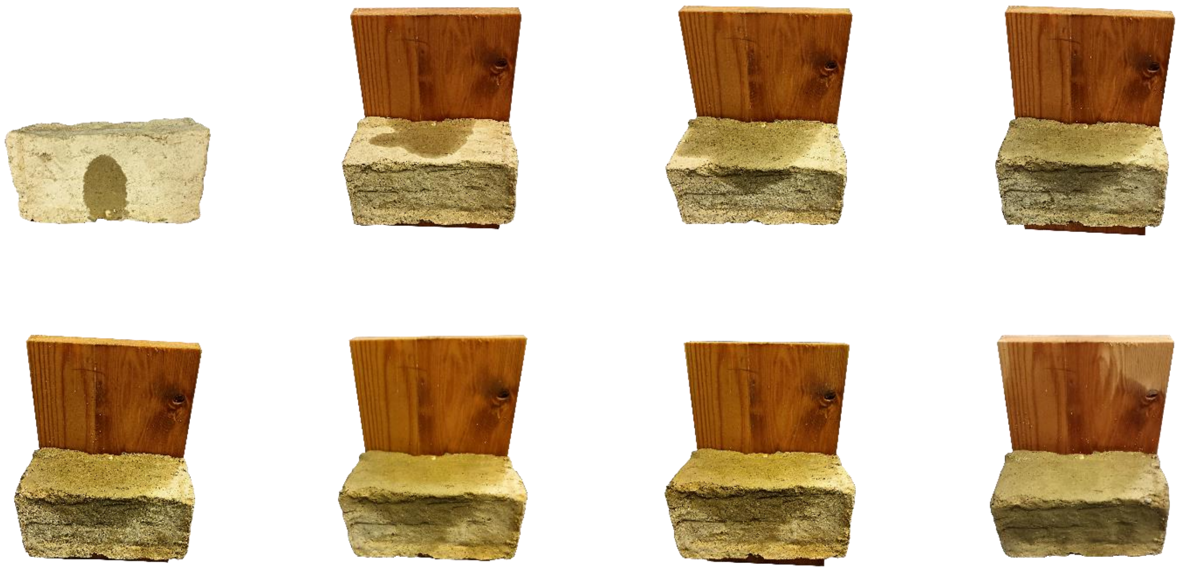
Round 1 - Albumen: Liquid



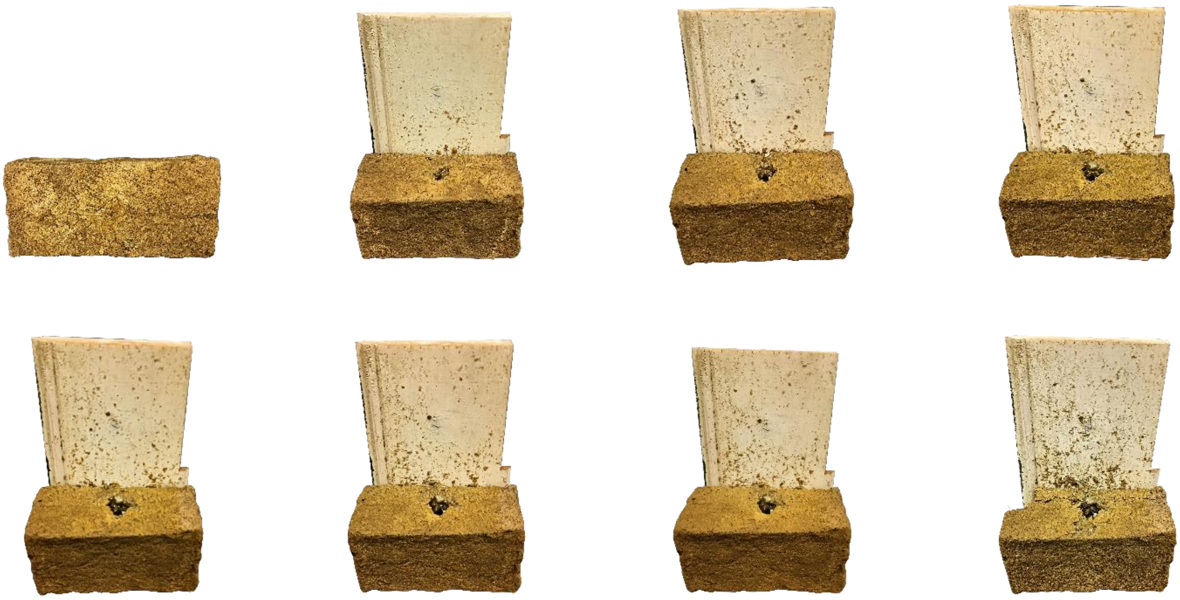
Round 1 - Albumen: Solid

Round 2 - Regular

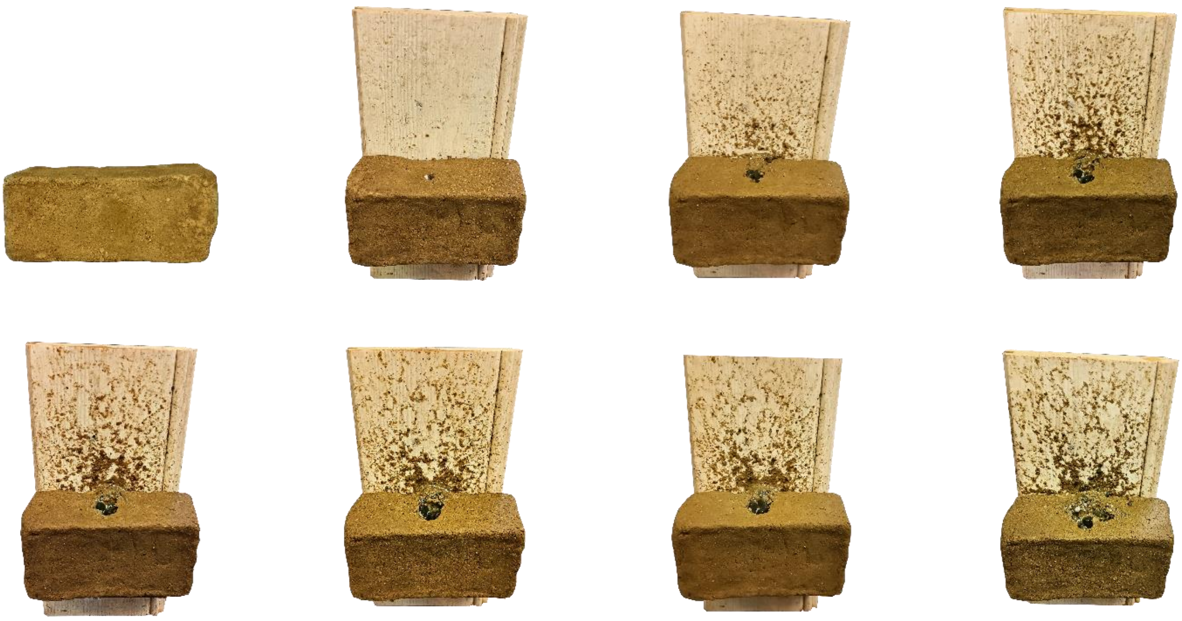
Round 2 - Cement



Round 2 - Sugar: 5%

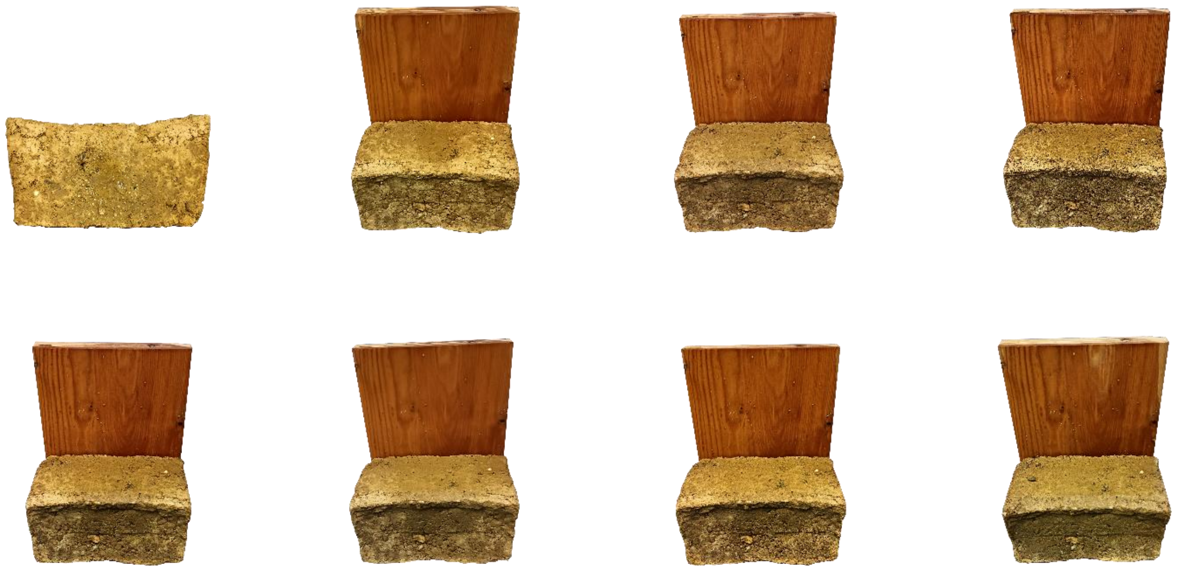


Round 2 - Sugar: 2%



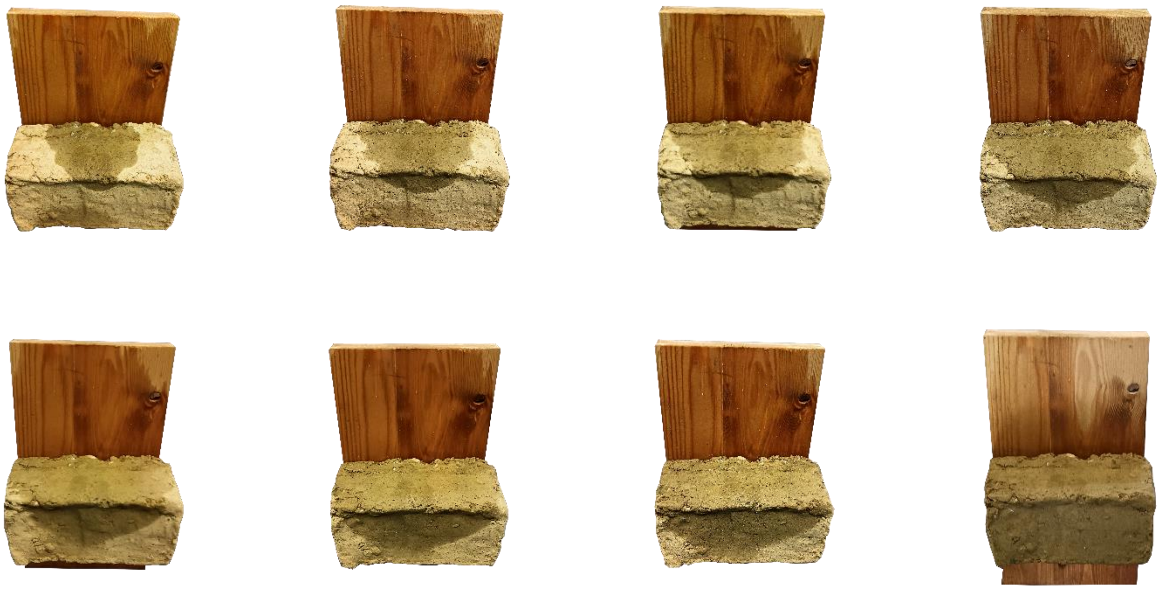
Round 2 - Albumen: Liquid

Round 2 - Albumen: Solid

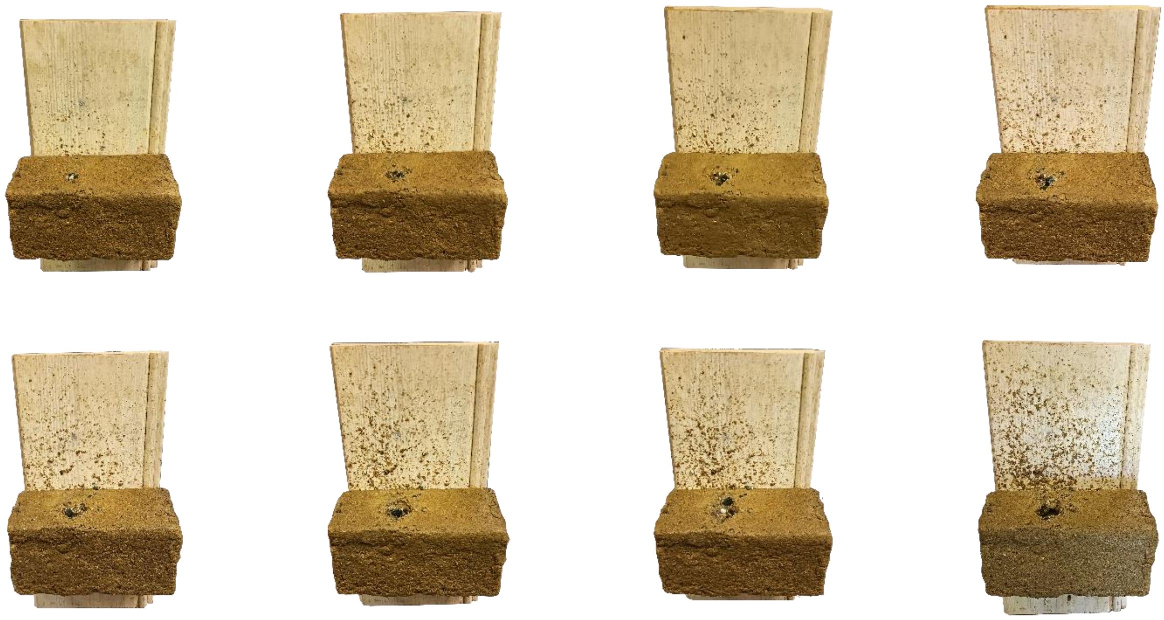


Round 3 - Regular

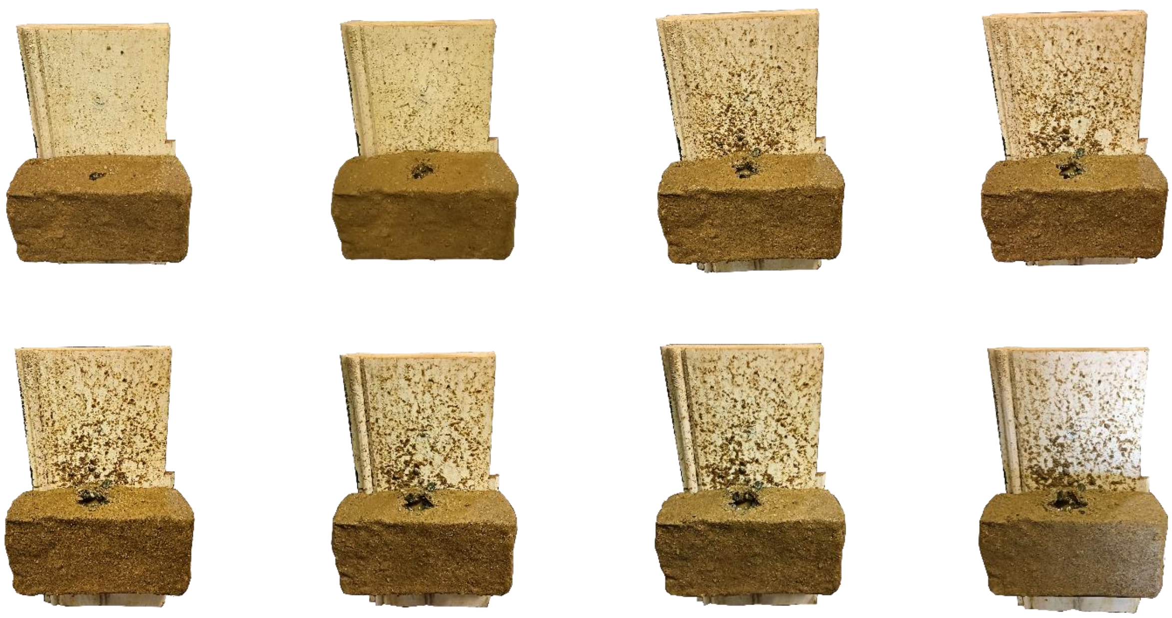
Round 3 - Cement



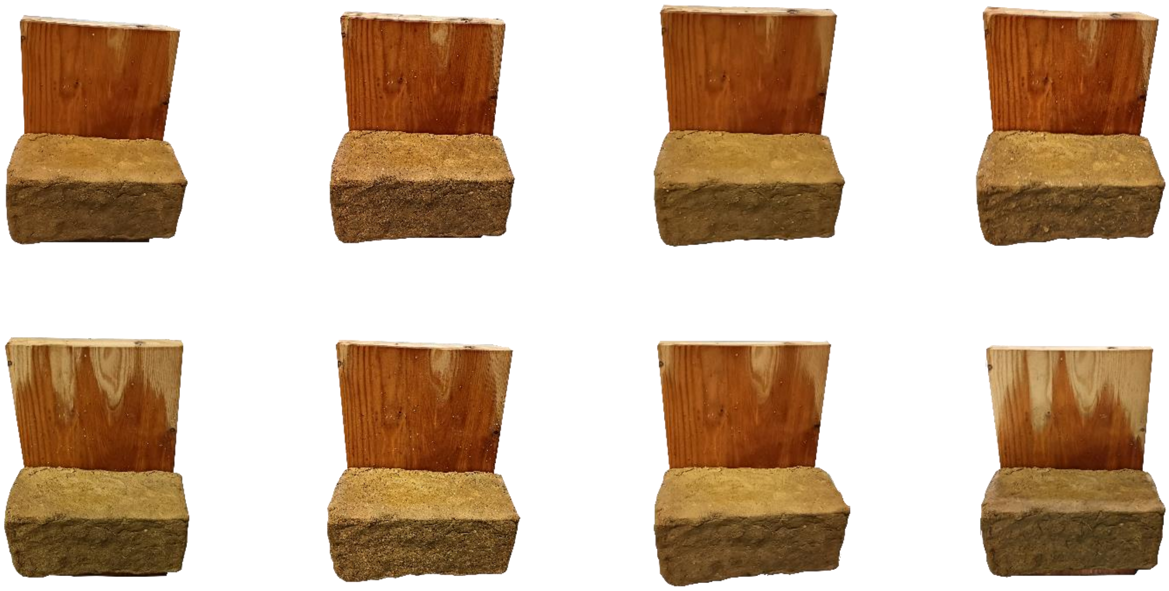
Round 3 - Sugar: 5%



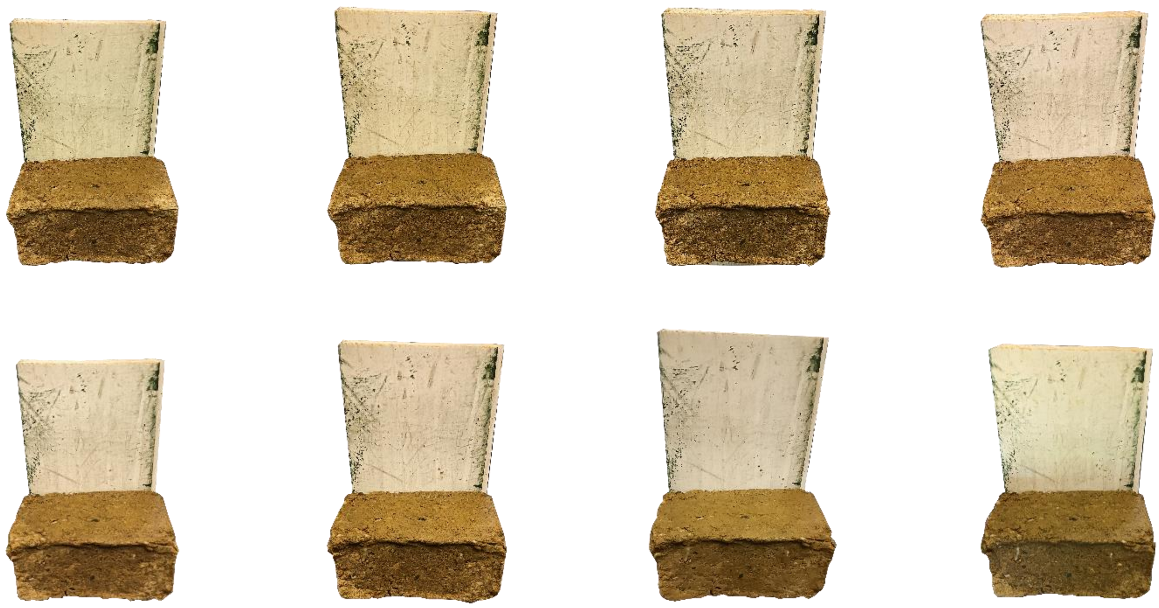
Round 3 - Sugar: 2%



Round 3 - Albumen: Liquid



Round 3 - Albumen: Solid



Detail of pitting

Round 1 Sugar: 2%

Round 3 Sugar: 2%

Round 2 Sugar: 2%

Round 2 Sugar: 5%

Round 1 Sugar: 5%

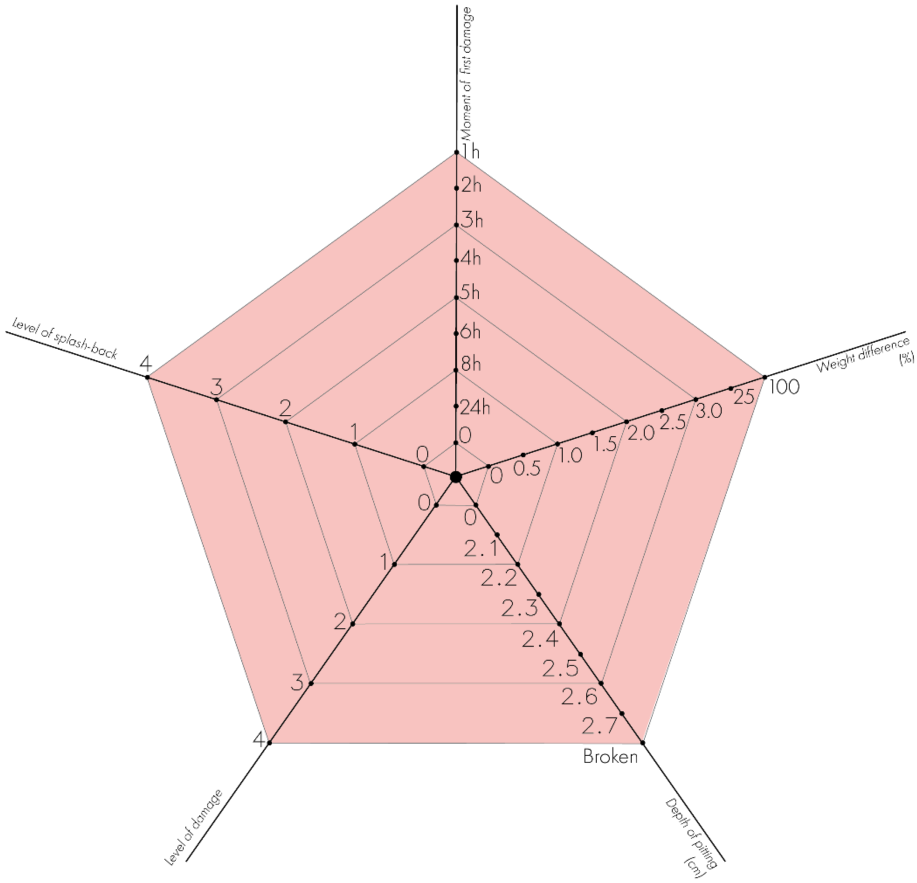
Round 3 Sugar: 5%

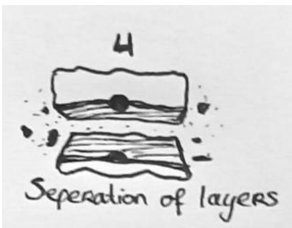
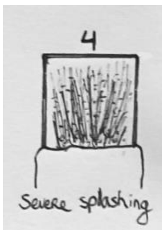
Appendix 16. Drip test – Results

Final findings: Regular, sample 1

Final findings

Sample number: 1
Sample type: Regular

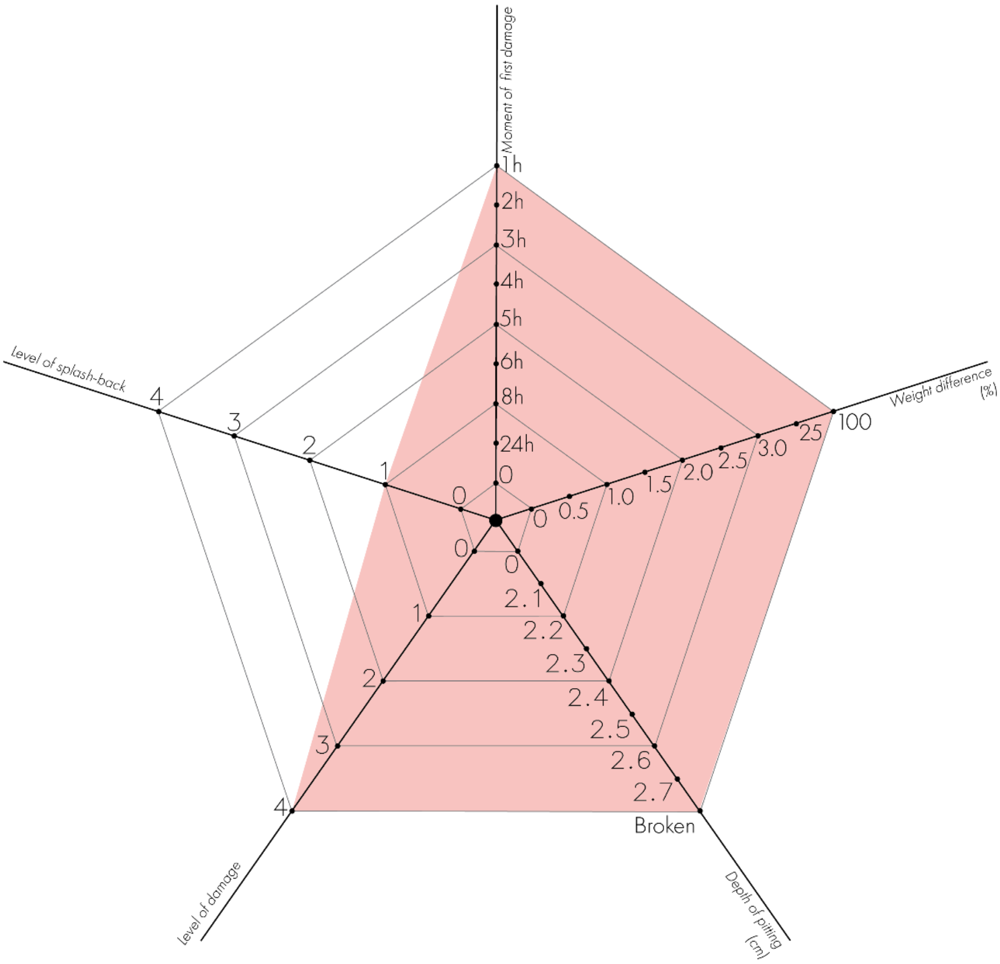


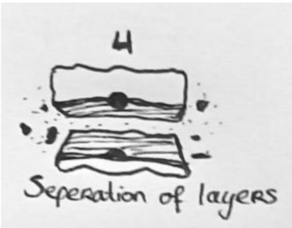
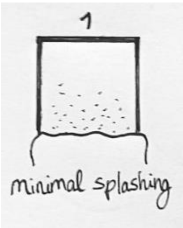
Category	Score	Visualisation
1. Moment of first damage	1h = 8/8	 
2. Weight difference	100% = 8/8	
3. Depth of pitting	Broken = 8/8	
4. Level of damage	4/4	
5. Level of splash-back	4/4	
Total	32/32	

Final findings: Regular, sample 2 & 3

Final findings

Sample number: 2, 3
Sample type: Regular

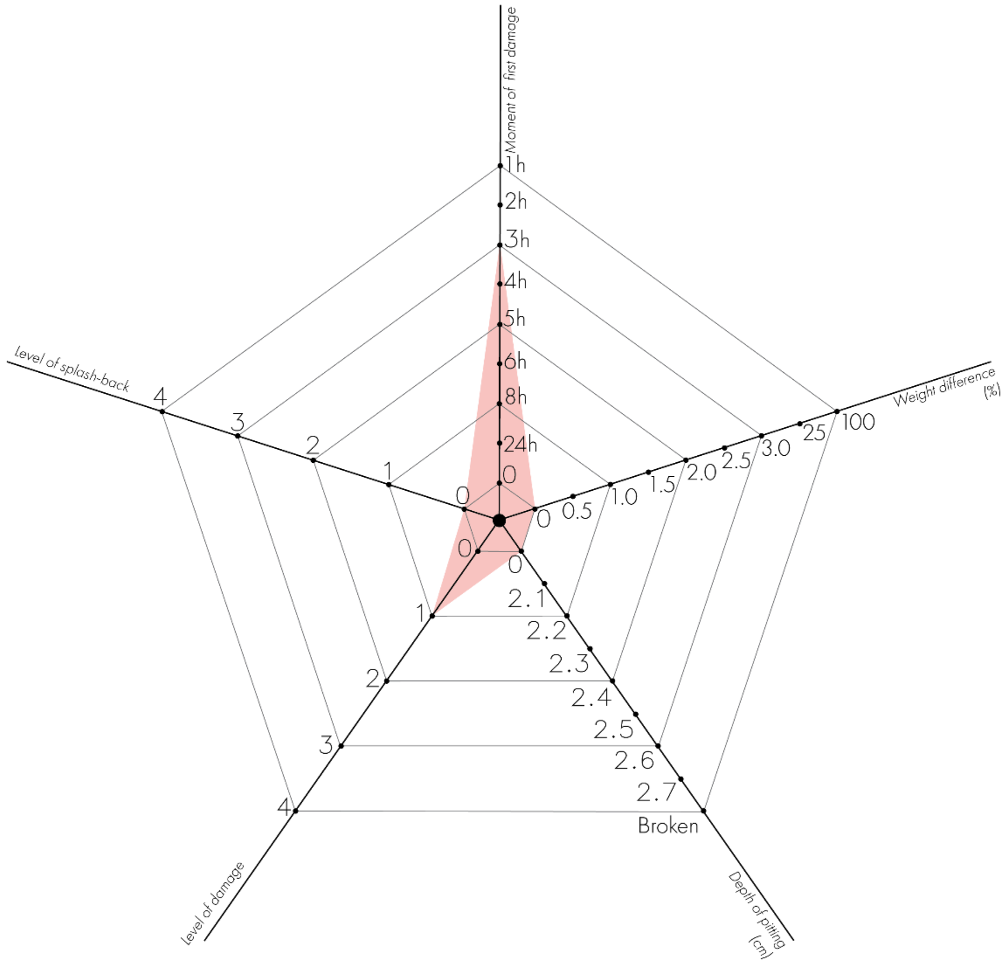


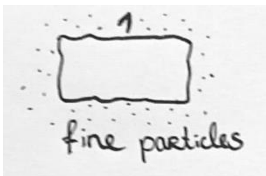
Category	Score	Visualisation
1. Moment of first damage	1h = 8/8	 
2. Weight difference	100% = 8/8	
3. Depth of pitting	Broken = 8/8	
4. Level of damage	4/4	
5. Level of splash-back	1/4	
Total	29/32	

Final findings: Cement, sample 1

Final findings

Sample number: 1
Sample type: Cement

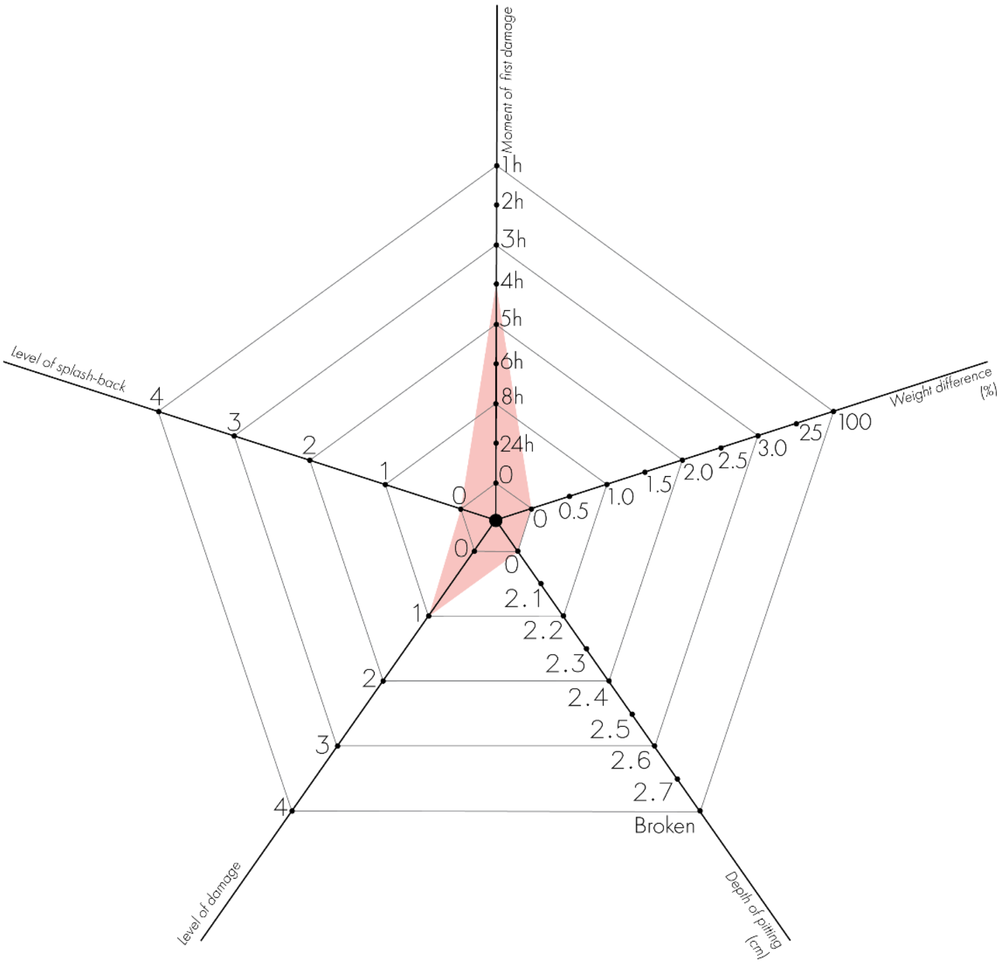


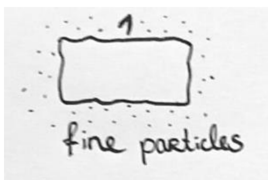
Category	Score	Visualisation
1. Moment of first damage	3h = 6/8	
2. Weight difference	Intact = 0/8	
3. Depth of pitting	Intact = 0/8	
4. Level of damage	1/4	
5. Level of splash-back	0/4	
Total	7/32	

Final findings: Cement, sample 2

Final findings

Sample number: 2
Sample type: Cement

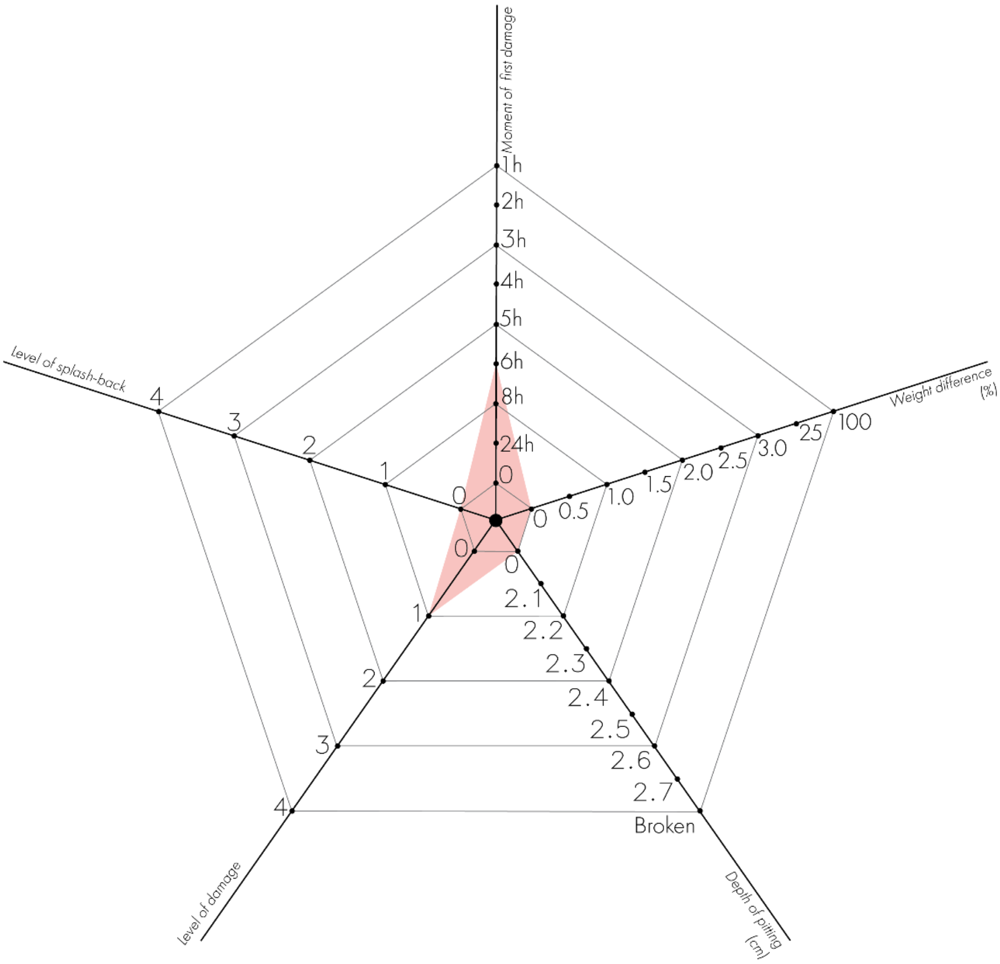


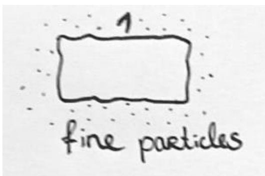
Category	Score	Visualisation
1. Moment of first damage	4h = 5/8	
2. Weight difference	Intact = 0/8	
3. Depth of pitting	Intact = 0/8	
4. Level of damage	1/4	
5. Level of splash-back	0/4	
Total	6/32	

Final findings: Cement, sample 3

Final findings

Sample number: 3
Sample type: Cement

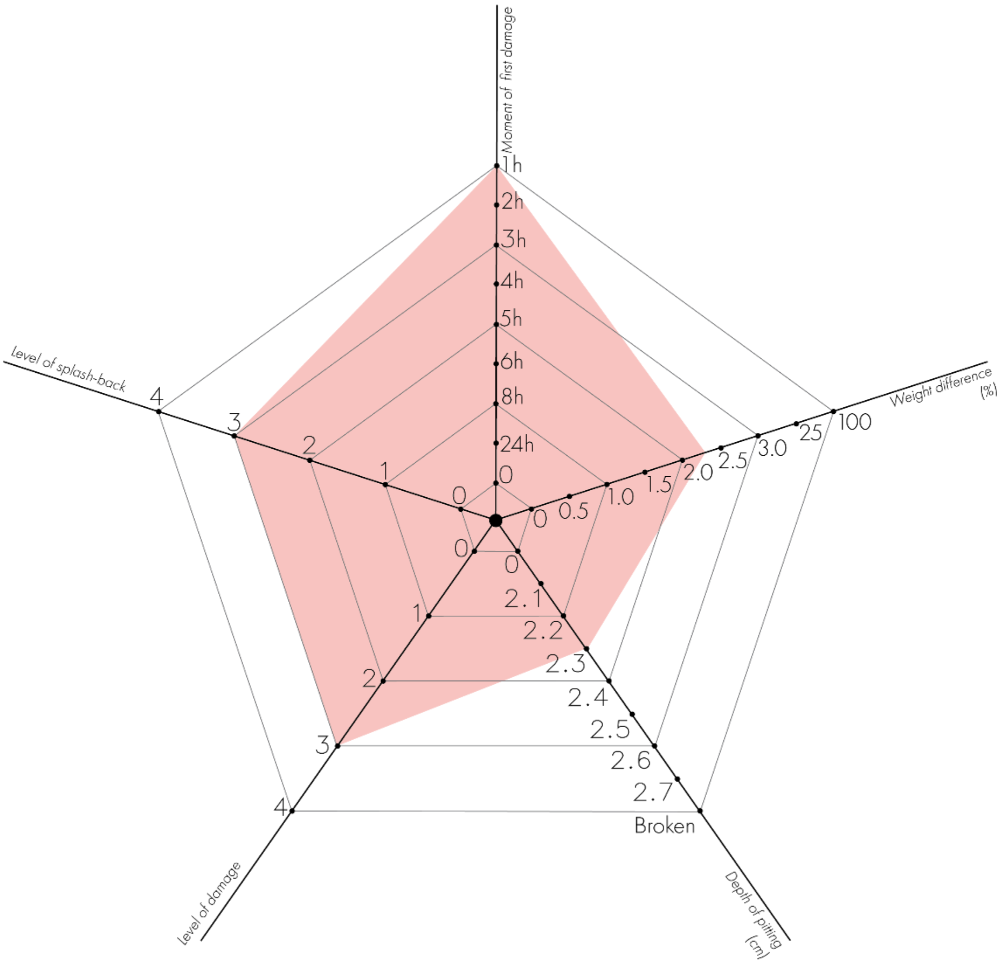


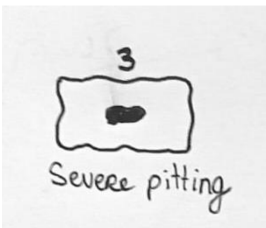
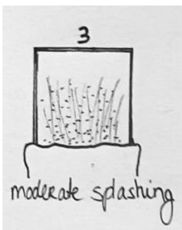
Category	Score	Visualisation
1. Moment of first damage	6h = 3/8	
2. Weight difference	Intact = 0/8	
3. Depth of pitting	Intact = 0/8	
4. Level of damage	1/4	
5. Level of splash-back	0/4	
Total	4/32	

Final findings: Sugar 5%, sample 1

Final findings

Sample number: 1
Sample type: Sugar: 5%

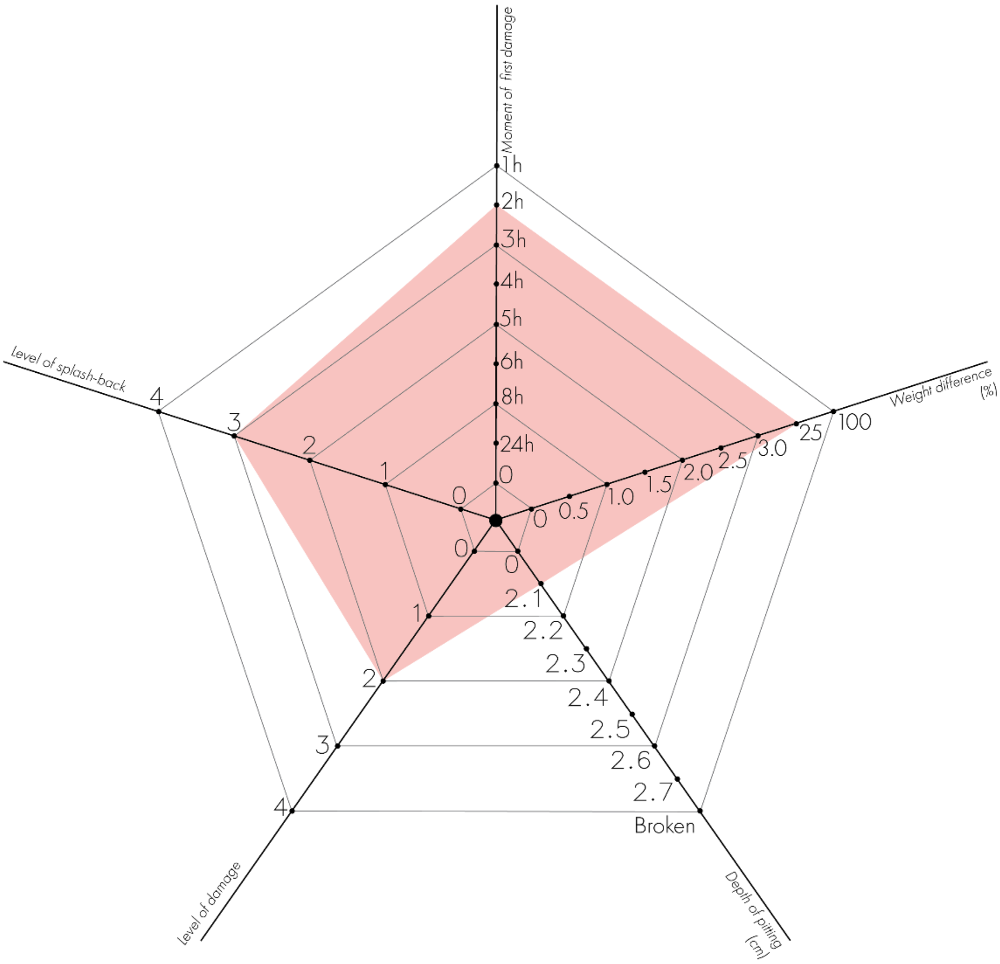


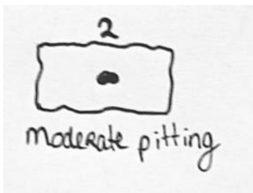
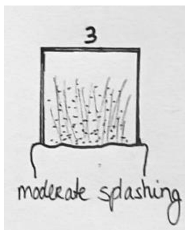
Category	Score	Visualisation
1. Moment of first damage	1h = 8/8	 
2. Weight difference	2.3% = 4.5/8	
3. Depth of pitting	2.3cm = 3/8	
4. Level of damage	3/4	
5. Level of splash-back	3/4	
Total	21.5/32	

Final findings: Sugar 5%, sample 2

Final findings

Sample number: 2
Sample type: Sugar: 5%

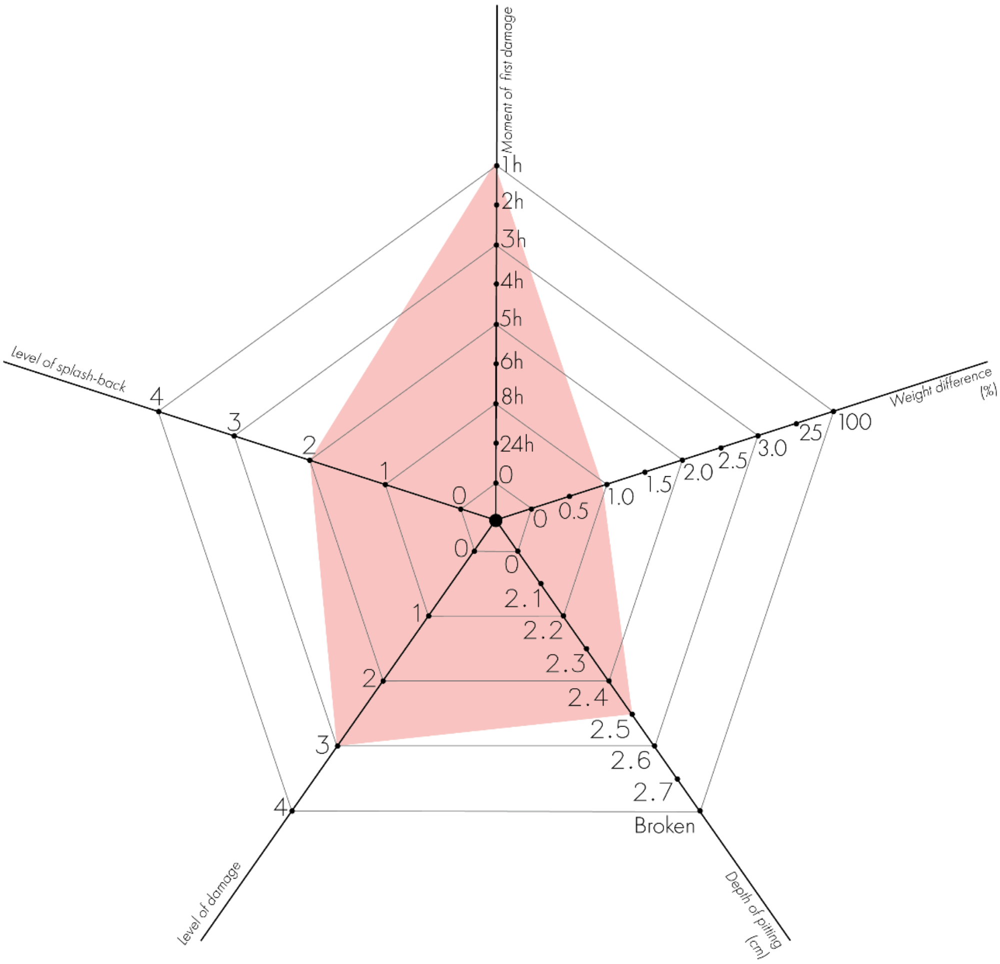


Category	Score	Visualisation
1. Moment of first damage	2h = 7/8	 
2. Weight difference	28.1% = 7/8	
3. Depth of pitting	2.1cm = 1/8	
4. Level of damage	2/4	
5. Level of splash-back	3/4	
Total	20/32	

Final findings: Sugar 5%, sample 3

Final findings

Sample number: 3
Sample type: Sugar: 5%

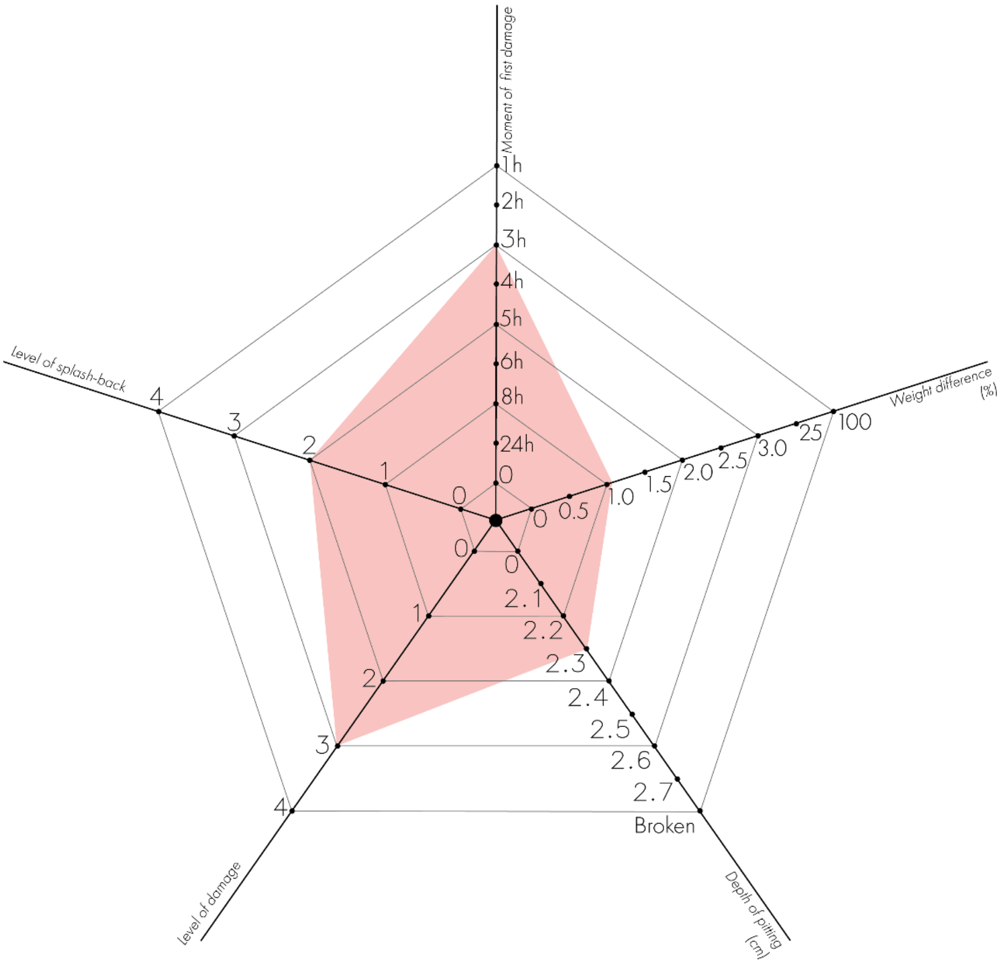


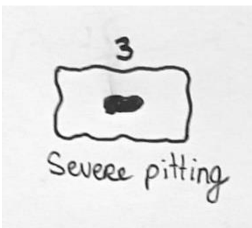
Category	Score	Visualisation
1. Moment of first damage	1h = 8/8	 
2. Weight difference	0.9% = 2/8	
3. Depth of pitting	2.5cm = 5/8	
4. Level of damage	3/4	
5. Level of splash-back	2/4	
Total	20/32	

Final findings: Sugar 2%, sample 1

Final findings

Sample number: 1
Sample type: Sugar: 2%

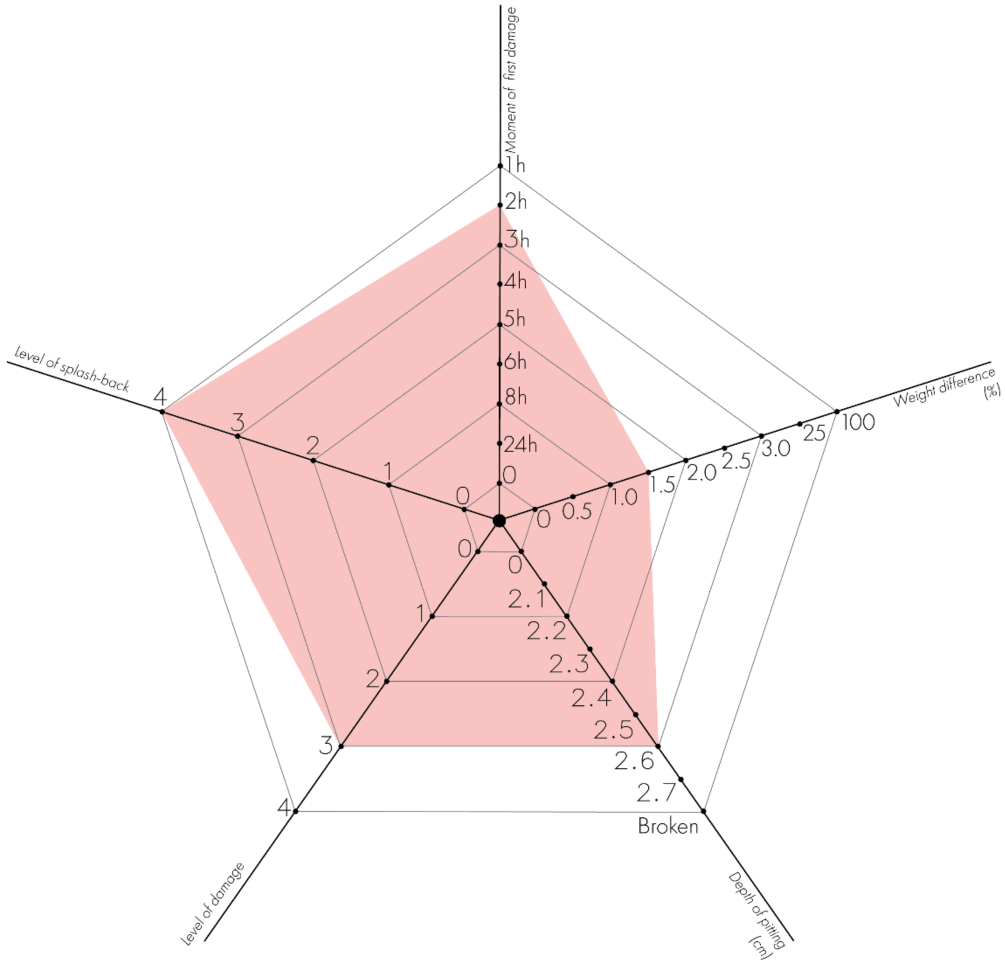


Category	Score	Visualisation
1. Moment of first damage	3h = 6/8	 
2. Weight difference	1.1% = 2/8	
3. Depth of pitting	2.3cm = 3/8	
4. Level of damage	3/4	
5. Level of splash-back	2/4	
Total	16/32	

Final findings: Sugar 2%, sample 2

Final findings

Sample number: 2
Sample type: Sugar: 2%

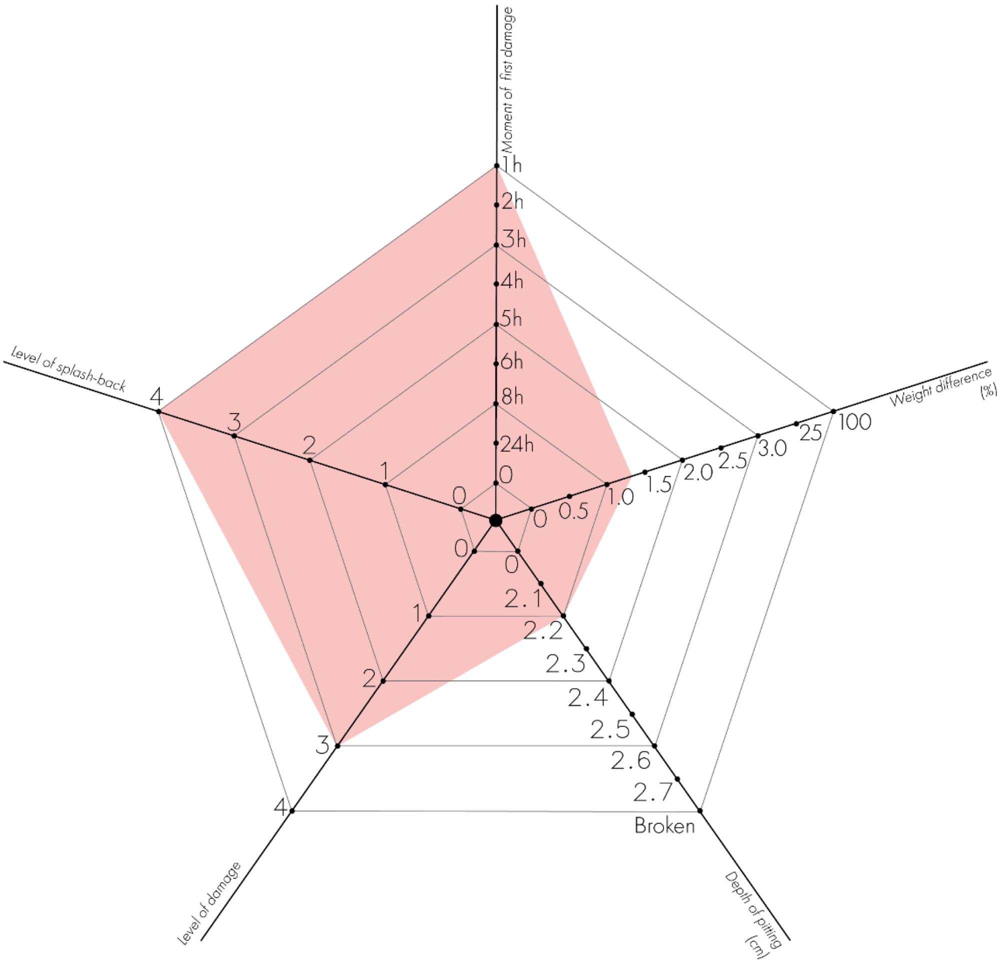


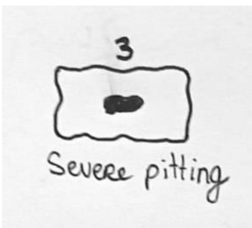
Category	Score	Visualisation
1. Moment of first damage	2h = 7/8	 
2. Weight difference	1.5% = 3/8	
3. Depth of pitting	2.6cm = 6/8	
4. Level of damage	3/4	
5. Level of splash-back	4/4	
Total	23/32	

Final findings: Sugar 2%, sample 3

Final findings

Sample number: 3
Sample type: Sugar: 2%

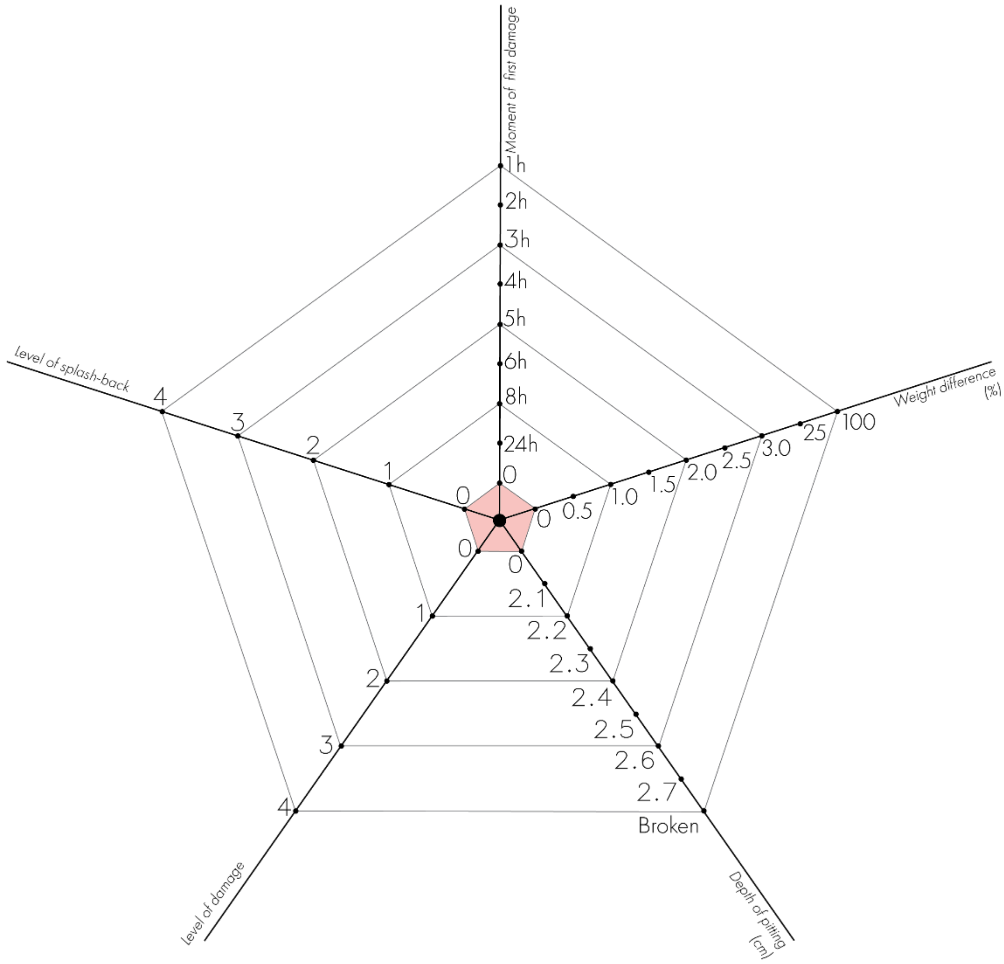


Category	Score	Visualisation
1. Moment of first damage	1h = 8/8	 
2. Weight difference	1.3% = 2.5/8	
3. Depth of pitting (cm)	2.2 = 2/8	
4. Level of damage	3/4	
5. Level of splash-back	4/4	
Total	19.5/32	

Final findings: Albumen liquid, sample 1, 2, 3

Final findings

Sample number: 1, 2, 3
Sample type: Albumen: Liquid

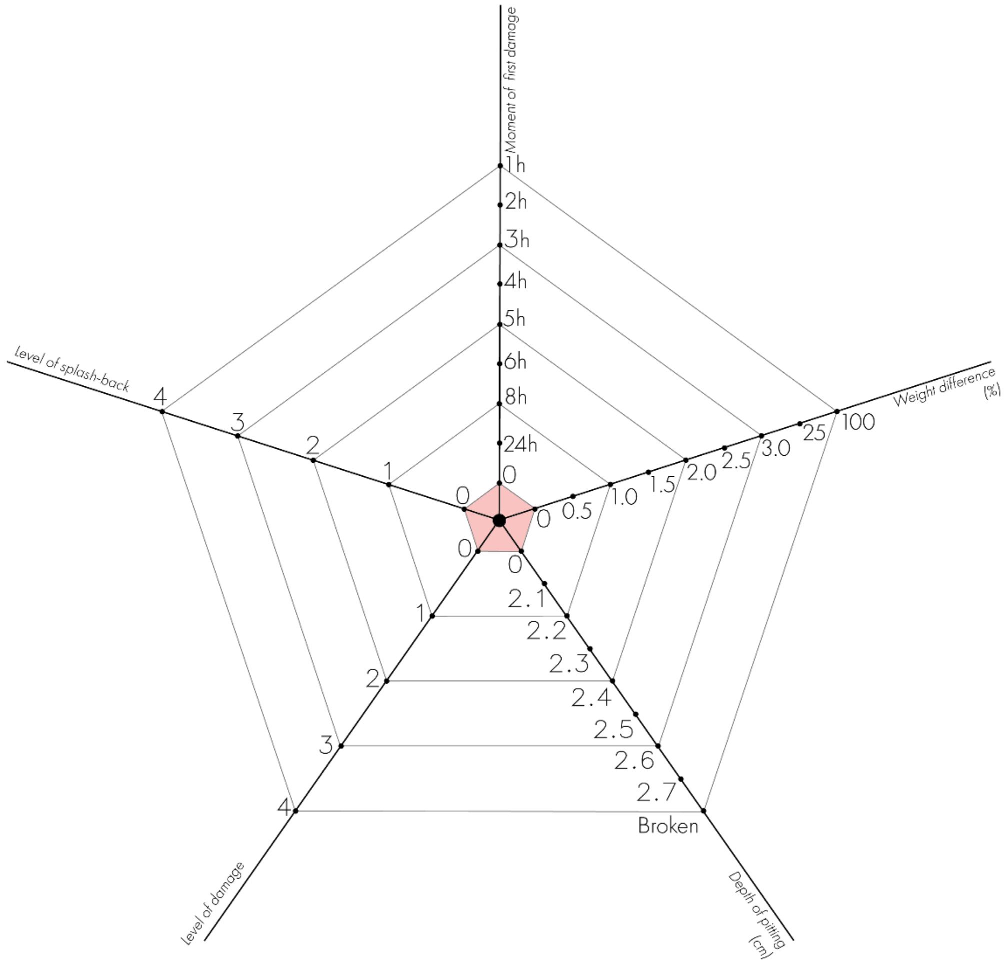


Category	Score	Visualisation
1. Moment of first damage	Intact = 0/8	*n/a*
2. Weight difference	Intact = 0/8	
3. Depth of pitting (cm)	Intact = 0/8	
4. Level of damage	Intact = 0/8	
5. Level of splash-back	Intact = 0/8	
Total	0/32	

Final findings: Albumen solid, sample 1, 2, 3

Final findings

Sample number: 1, 2, 3
Sample type: Albumen: Solid



Category	Score	Visualisation
1. Moment of first damage	Intact = 0/8	*n/a*
2. Weight difference	Intact = 0/8	
3. Depth of pitting (cm)	Intact = 0/8	
4. Level of damage	Intact = 0/8	
5. Level of splash-back	Intact = 0/8	
Total	0/32	

Appendix 17. Spray test – Images

Round 1 - Regular

20 Minutes

40 Minutes

60 Minutes

80 Minutes

100 Minutes

120 Minutes

Round 1 - Cement

20 Minutes

40 Minutes

60 Minutes

80 Minutes

100 Minutes

120 Minutes

Round 1 - Sugar: 5%

20 Minutes

40 Minutes

60 Minutes

80 Minutes

100 Minutes

120 Minutes

Round 1 - Sugar: 2%

20 Minutes

40 Minutes

60 Minutes

80 Minutes

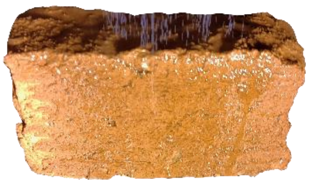
100 Minutes

120 Minutes

Round 1 - Albumen: Liquid

20 Minutes

120 Minutes



Round 1 - Albumen: Solid

20 Minutes

120 Minutes

Round 2 - Regular

20 Minutes

40 Minutes

60 Minutes

80 Minutes

100 Minutes

120 Minutes

Round 2 - Sugar: 5%

20 Minutes

40 Minutes

60 Minutes

80 Minutes

100 Minutes

120 Minutes

Round 2 - Sugar: 2%

20 Minutes

40 Minutes

60 Minutes

80 Minutes

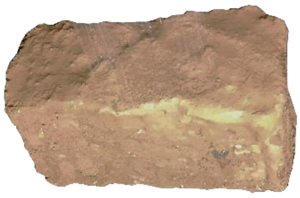
100 Minutes

120 Minutes

Round 2 - Albumen: Liquid

20 Minutes

120 Minutes



Round 2 - Albumen: Solid

20 Minutes

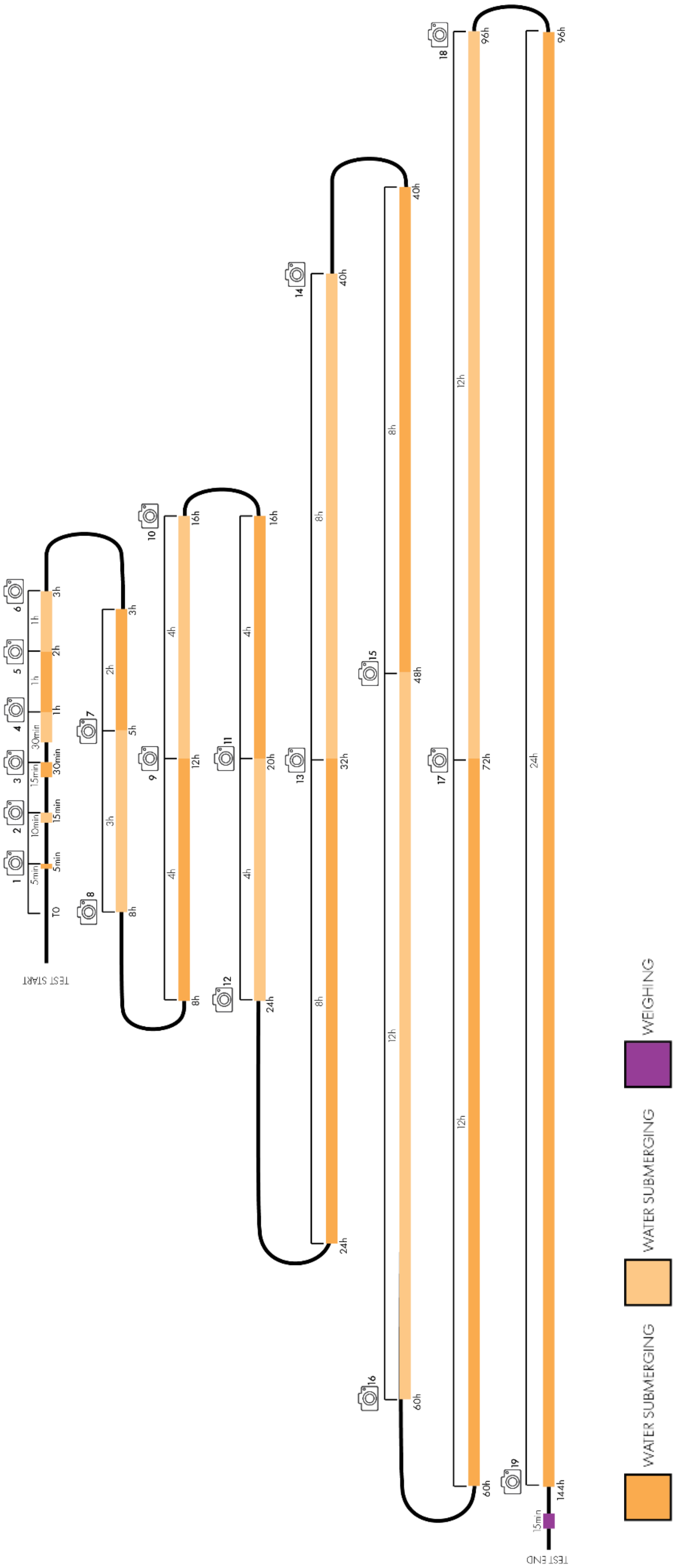
120 Minutes

Round 2 - Cement

20 Minutes

120 Minutes

Appendix 18. Moisture absorption test – Timeline



Appendix 19. Moisture absorption test – Images

0 - Start

1 - 5 minutes

2 - 15 minutes

3 - 30 minutes

4 - 1 hour

5 - 2 hours

6 - 3 hours

7 - 5 hours

8 - 8 hours

9 - 12 hours

10 - 16 hours

11 - 20 hours

12 - 24 hours, 1 day

13 - 32 hours

14 - 40 hours

15 - 48 hours, 2 days

16 - 60 hours

17 - 72 hours, 3 days

18 - 96 hours, 4 days

19 - 144 hours, 6 days

Appendix 20. Freeze and thaw test – Results