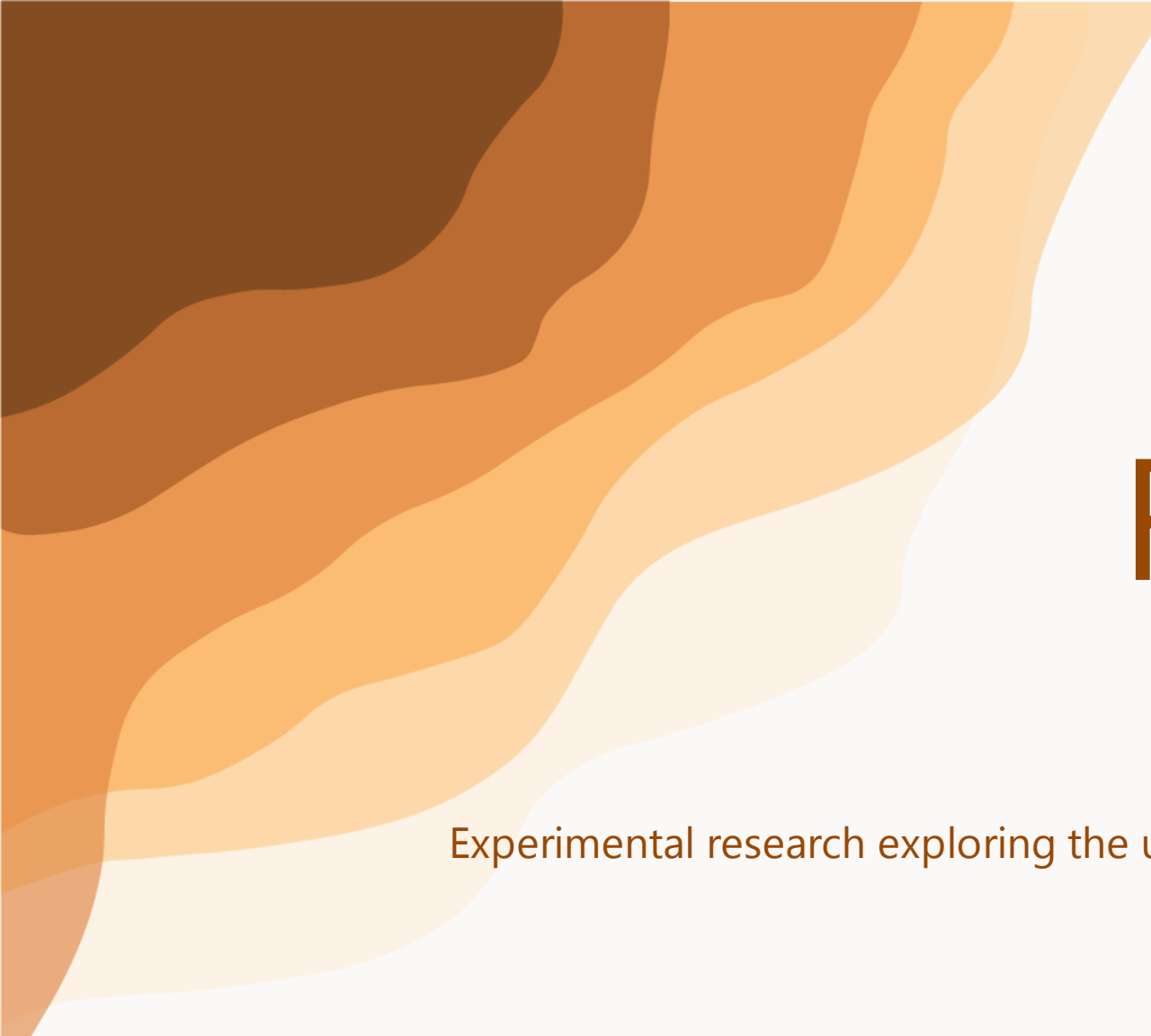




Bio-based Binders for Rammed Earth Construction

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

Fieke Konijnenberg

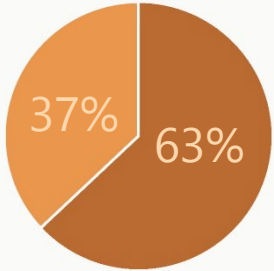
25-06-2024

First mentor:
Second mentor:
Advisors:

Olga Ioannou
Wido Quist
abt

P5 - Building Technology
MSc Architecture, Urbanism and Building Sciences

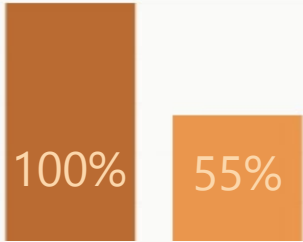
INTRODUCTION



Built environment produces 37% of total global emissions. Can be split up in:

- Operational carbon (building use)
- Embodied carbon (building construction)

(UNEP, 2023)



Bio-based materials produce 45% LESS emissions, compared to inorganic materials.

(Zuiderveen et al, 2023)



Reduce overall emissions + Use bio-based materials =

- Rediscovery heritage architecture

(Birznieks, 2013)

Oldest (bio-based) construction material =

- Raw earth

(Dethier, 2020)

RAW EARTH ARCHITECTURE

- Oldest building material. (Birznieks, 2013)
- 50% to 25% Modern dwellings. (Gantopoulou, 2014) (Van Gorp, 2018)
- Every continent, climate, environment. (Dethier, 2020)
- Local know-how & skills. (Norton, 1997)

BENEFITS

- Availability worldwide. (Norton, 1997)
- Indoor climate; temperature, humidity. (Birznieks, 2013)
- Air quality; no VOC, smell absorption. (Van Gorp, 2018) (Dethier, 2020)
- Environmental costs; lowest NIBE score. (Birznieks, 2013)
- Social environment; cultural identities, local education. (Dethier, 2020)

Wheel of 12
Adapted from

Wheel of 12 technique:
Adapted from CRATerre,
1994 (Grunacker, 2021)

RAMMED EARTH

Material:

Moist mixture of sand, clay, silt, aggregates, and potential binders.

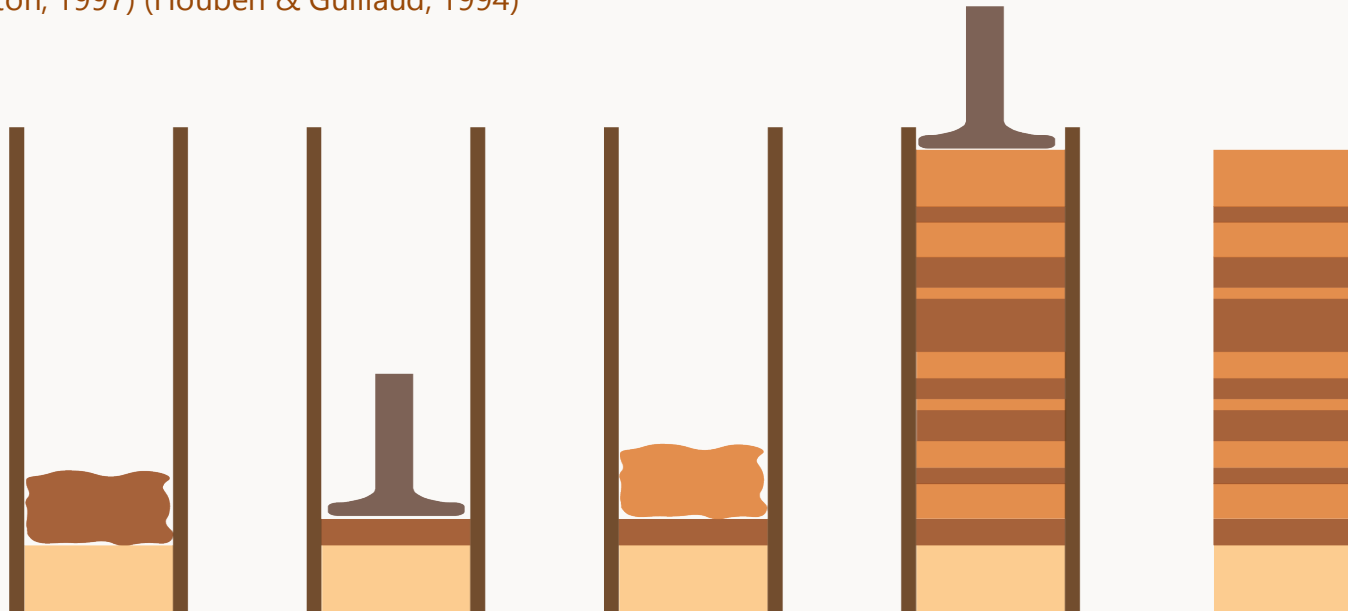
Construction technique:

Layers compacted in formwork using rammers, left to harden.

Product:

In-situ, monolithic, self-supporting, load-bearing, construction.

(Birznieks, 2013) (Norton, 1997) (Houben & Guillaud, 1994)



RAMMED EARTH – DRAWBACKS

- Sensitive to frost damage *

(Houben & Guillaud, 1994)

- Sensitive to water damage *

(Houben & Guillaud, 1994)

- Poor thermal insulation

(Norton, 1997)

- Lack of building norm required compressive strength *

(Van Gorp, 2018)

- In-situ construction: weather conditions

(Ganotopoulou, 2014)

- In-situ construction: soil workability *, manpower, time consuming

(Dethier, 2020)

- Prefab construction: increased embodied energy of structure

(Ganotopoulou, 2014)



***Research aim**

PROBLEM STATEMENT



Industrial revolution → Population surge → Increase housing demand → Rapid housing construction

Industrial revolution → Mechanically produced materials (Bricks, concrete, steel, etc)

(Sgouropoulou, 2013)



Rapid housing construction + Industrialised materials

→ Dwindling use of heritage materials

→ Building norms → Excluded: Heritage materials.

(Ganotopoulou, 2014)



Exclusion building norms + Minimal use heritage materials

→ Knowledge loss heritage materials

→ Inorganically reinforced rammed earth

(Cockram, 2018)

RESEARCH OBJECTIVES



HERITAGE

- Heritage knowledge rammed earth → Historic relevance & Possible material enhancements
- Heritage knowledge binders → Matrix overview intended use of binders
- Possible bio-based binders for desired material enhancement

Possible material enhancements + Possible binders →

EXPERIMENTAL RESEARCH

- Effect of binder on rammed earth performance
- Comparison rammed earth with & without binders:
(bio-based binders & cement binder)

→ **SEARCH FOR SUSTAINABLE BUILDING MATERIAL**



RESEARCH QUESTIONS

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?

BIO-BASED BINDERS – HISTORIC

Name – Historic use – Function – Location – Score – Source

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

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

BIO-BASED BINDERS – MATRIX

RESEARCH AIM

1. Bio-based (GO – NO GO)
2. Low cost (GO – NO GO)
3. Availability (GO – NO GO)
4. Locally available (GO – NO GO)
5. Sustainable acquisition (GO – NO GO)
6. Sustainable production (GO – NO GO)
7. Recyclability (GO – NO GO)
8. Waste-stream (-, 0, +)
9. Material acceptance (-, 0, +)

MATERIAL ENHANCEMENTS

10. Compressive strength (GO – NO GO)
11. Plasticity and workability (-, 0, +)
12. Water repellence (-, 0, +)
13. Resistance to freeze-thaw cycles (-, 0, +)

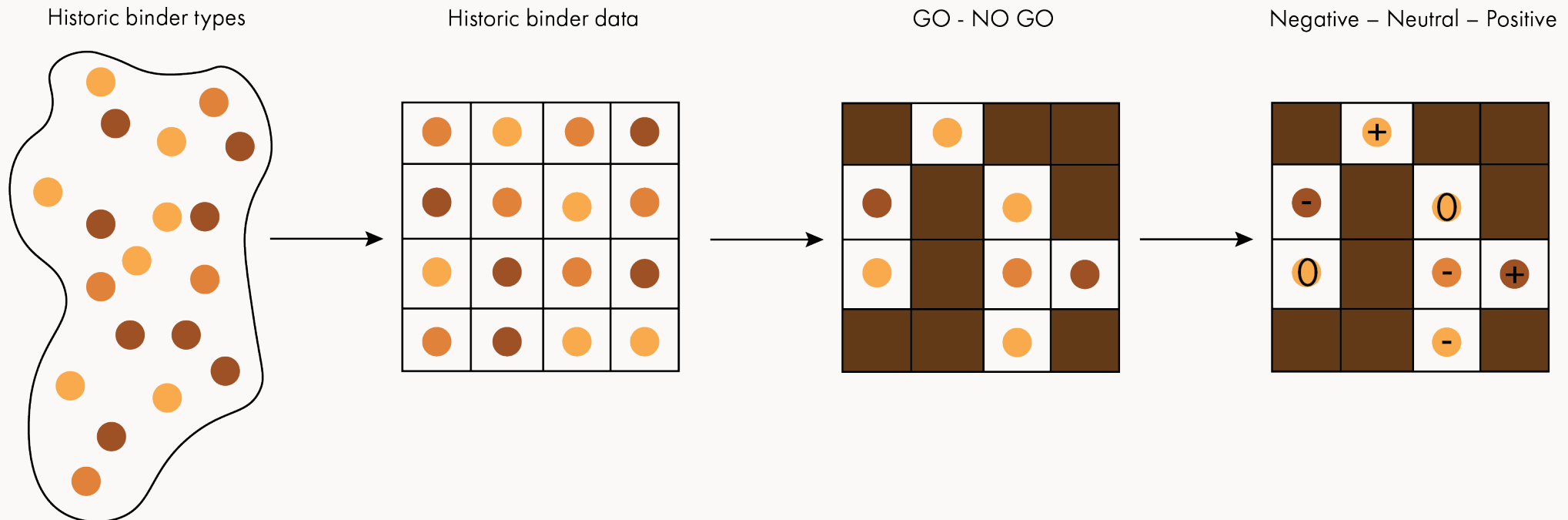
BIO-BASED BINDERS – MATRIX

1	2	3	4	5	6
Soy	3	His.		1	3
Seaweed	3	His.		-1	2
Beer	3			0	1
Vegetable juice	3			-1	0
Keratin, plant	3	His.		0	3
Tannin	3	His.		1	3

* See appendices 3-9.

GO = Green
NO GO = Orange

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



BIO-BASED BINDERS – OPTIONS

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

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

HIGHEST SCORING

- Plant mucilage
- Egg variations
- Jaggery = cane sugar
- Tannins
- Vegetable ash

BIO-BASED BINDERS – SAMPLING

EGG VARIANTS

- Yolk + Albumen
- Yolk
- Albumen, liquid
- Albumen, dehydrated



SUGAR VARIANTS

- Granulated beet sugar
- Beet sugar syrup
- Granulated beet sugar (80) + beet sugar syrup (20)
- Granulated beet sugar (50) + beet sugar syrup (50)



SAMPLING - RAMMED EARTH MIXTURE



TIERRAFINO RAMMED EARTH MIXTURE

- Münster, Germany
- Mixture type brown
- Aggregate size 0-16mm



BIG BAG

- 1m³
- 1000-1200kg
- ≈ 0.5m³ rammed
- 2300 kg/m³ rammed



SAMPLING - SET-UP

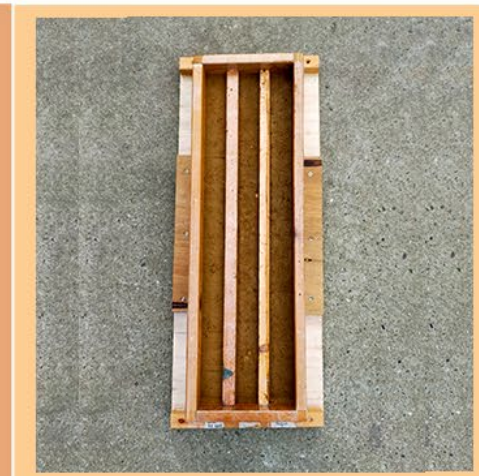
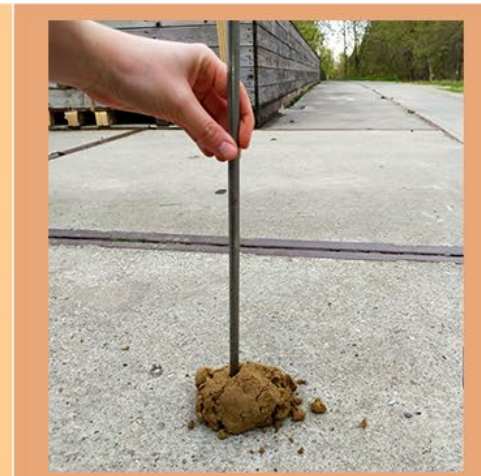
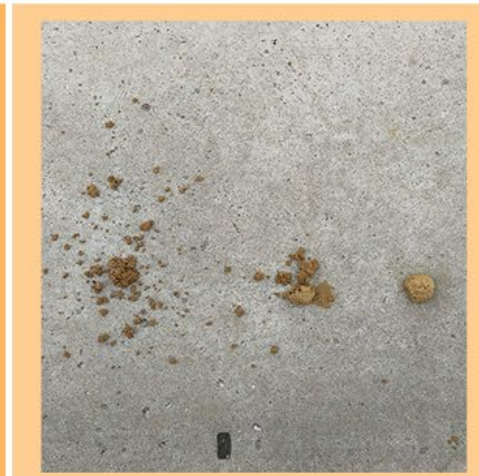


THE GREEN VILLAGE

- Garage box
(Indoors, heated to +/- 20 °C)
- Big Bag sampleem
- Bio-based binders
- Cement
- Worktable
- Formworks
- Buckets
- Mixing bowls
- Measuring bowls
- Scale 2x (accuracy 1g & 0.1g)
- Knife, scissor, blender
- Shovel, scoops, spoons
- Measuring tape, sticks
- Double boiled linseed oil
- Paint-tray, brushes

TESTING 1 – MIXTURE COMPOSITION

1. Water content - Workability test EN 1015-3	2. Water content - Drop test John Norton	3. Water content - Bar test John Norton	4. Shrinkage - Shrink box/Alcock test SNZ4298 John Norton	5. Plasticity - Sausage or cigar test John Norton
- Acquire 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.	- 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.	- Acquire 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.	- 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 separated 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.	- Form clay roll, sized with diameter approximately 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



TESTING 1 – MIXTURE COMPOSITION

1. Water content - Workability test

EN 1015-3

- Acquire 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 (30s).
- 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

- Acquire 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 separated 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 approximately 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 = 8-15cm (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



RATIO – DETERMINATION

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)

SAMPLE WEIGHT

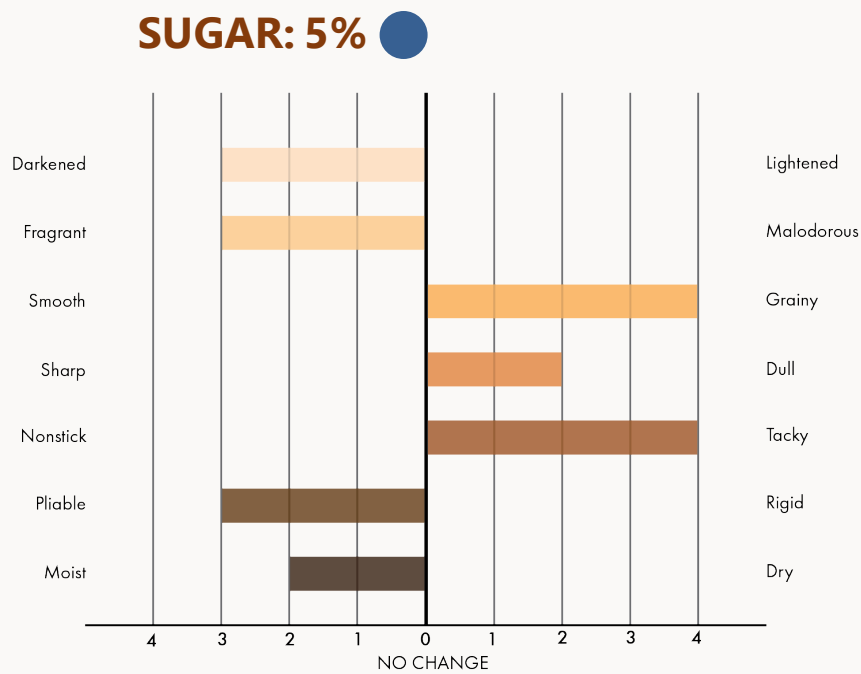
Total: 100 grams

RECOMMENDED PERCENTAGES

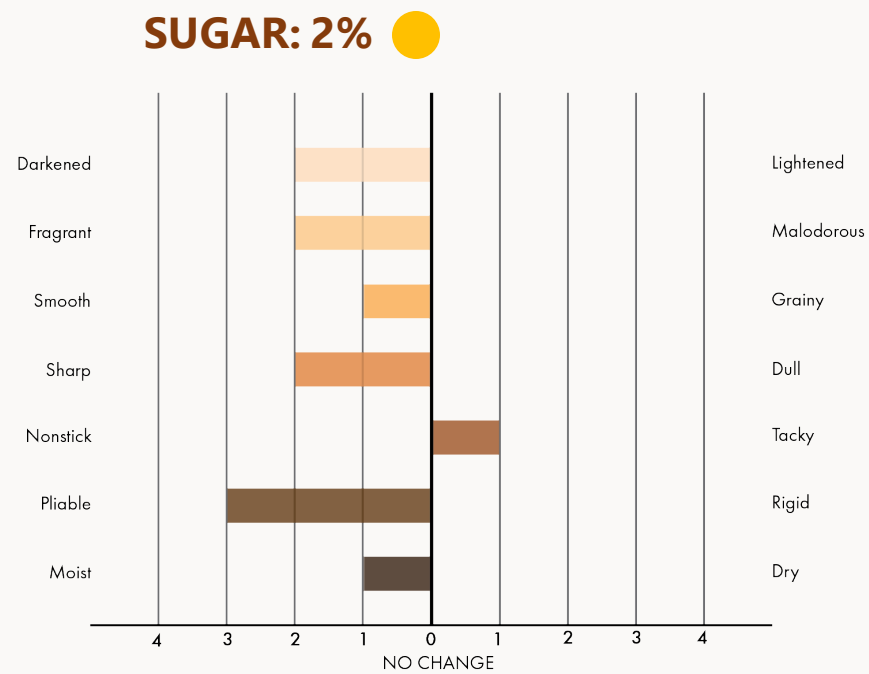
- 0.25% binder optimum (Ramesh et al., 2017)
- 10% binder maximum (HiveEarth, n.d.)

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
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

RATIO – SUGAR – OBSERVATIONS

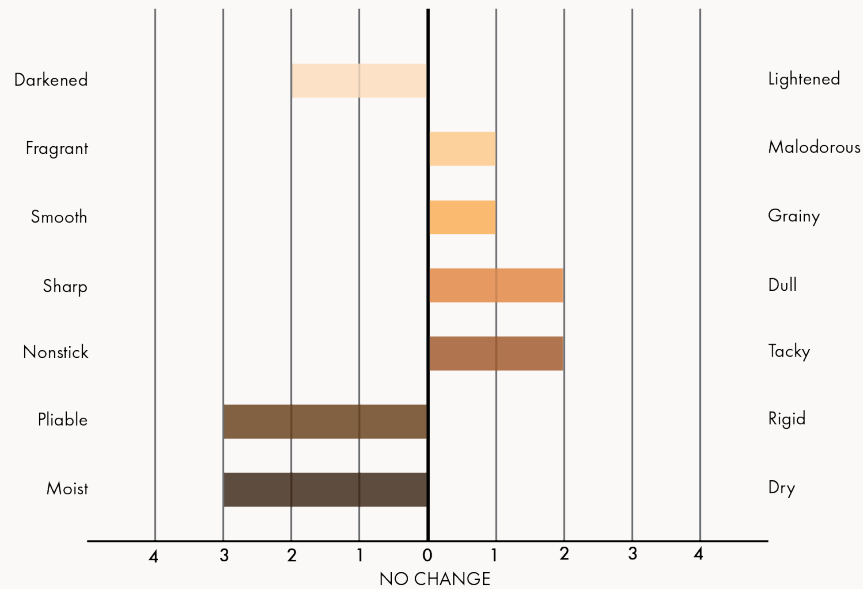


COLOUR
SMELL
TEXTURE
EDGES
ADHESION
PLIABILITY
MOISTURE LEVEL



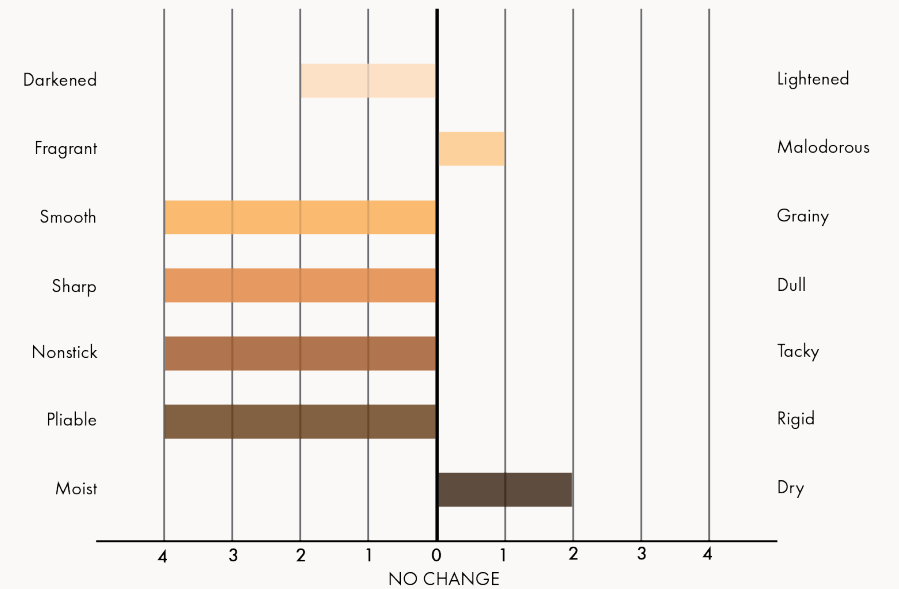
RATIO – EGG – OBSERVATIONS

ALBUMEN: LIQUID ●



COLOUR
SMELL
TEXTURE
EDGES
ADHESION
PLIABILITY
MOISTURE LEVEL

ALBUMEN: SOLID* ●



* SOLID = DEHYDRATED

RATIO – CEMENT



RATIO – SUGAR – GRANULATED



RATIO – EGG – ALBUMEN: LIQUID



EGG – ALBUMEN: SOLID



SAMPLES

FORMWORK



DRYING



SAMPLES



TESTING 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 weight 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.
- Acquire 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).
- Acquire 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).
- Acquire 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:

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



TESTING 2 – MECHANICAL CHARACTERISTICS

5. 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 weight 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.
- Acquire sharp probe.
- Push probe in samples from a distance of 5 to 10cm at a force of 1.5kg.
- Compare to predetermined acceptability norms.



9. Simple strength test

John Norton

- Form compressed earth brick sample group (CEB).
- Acquire 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.



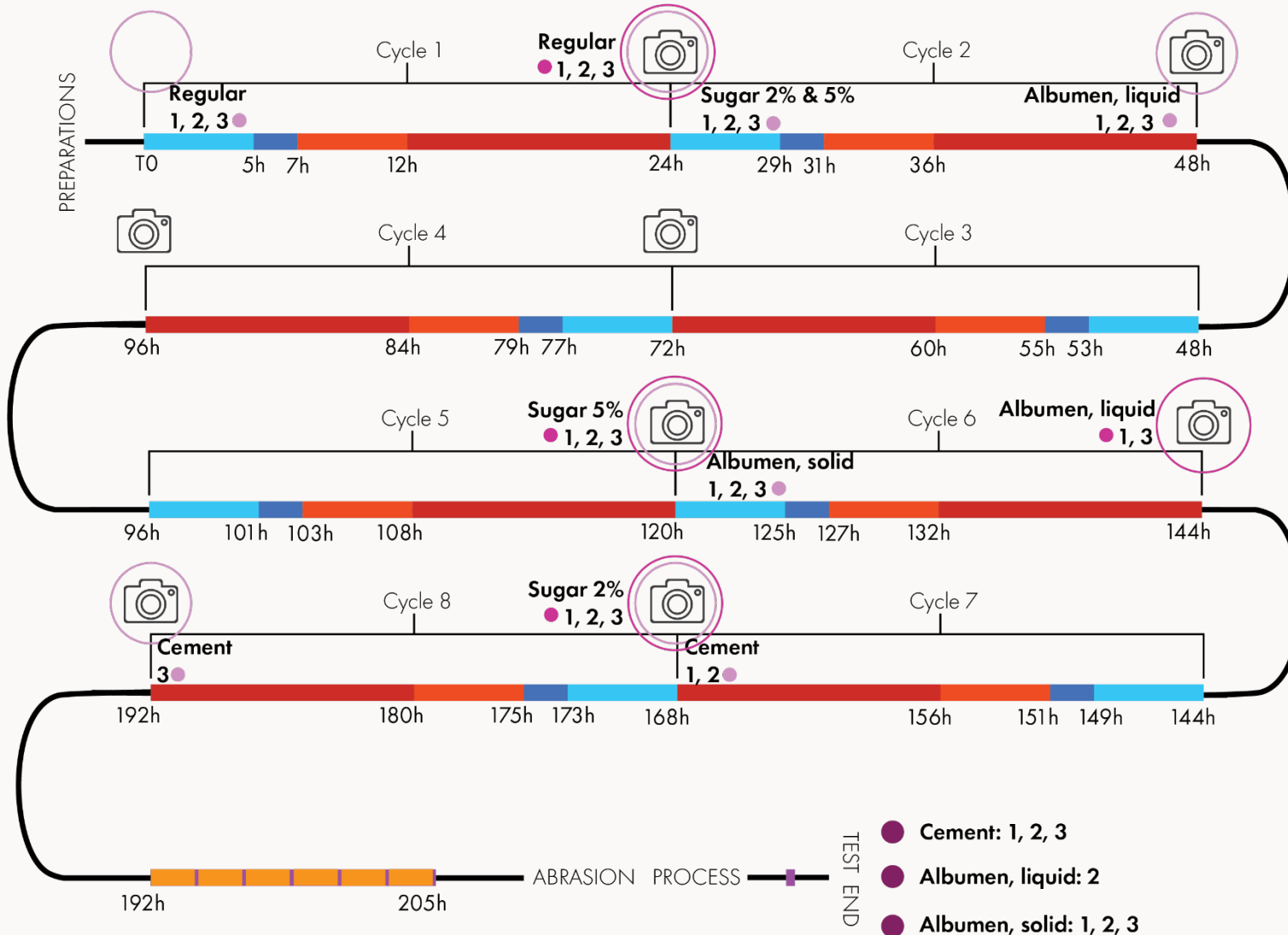
10. Modulus of rupture test

John Norton

- Form compressed earth brick sample group (CEB).
- Acquire 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:

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


MECHANICAL – WETTING AND DRYING



WETTING AND DRYING – RESULTS

1. 5 HOURS



2. 10 HOURS



3. 15 HOURS



4. 20 HOURS



5. 25 HOURS



6. 30 HOURS



7. 35 HOURS



8. 40 HOURS



WETTING AND DRYING – RESULTS – SUGAR

ROUND 2 – 10 HOURS

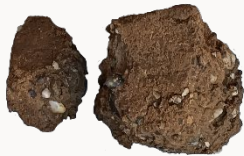


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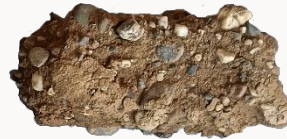


2%

ROUND 3 – 15 HOURS

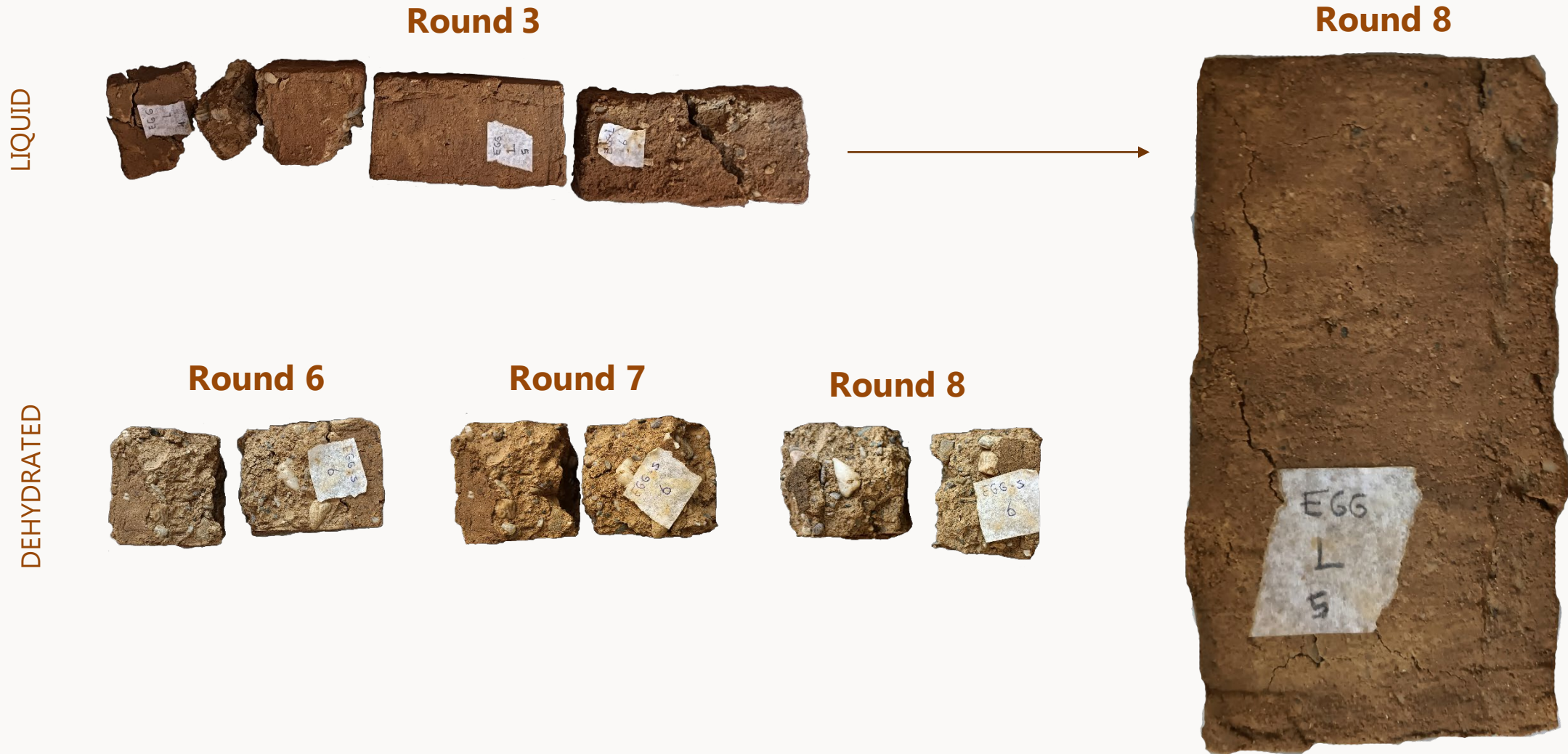


5%



2%

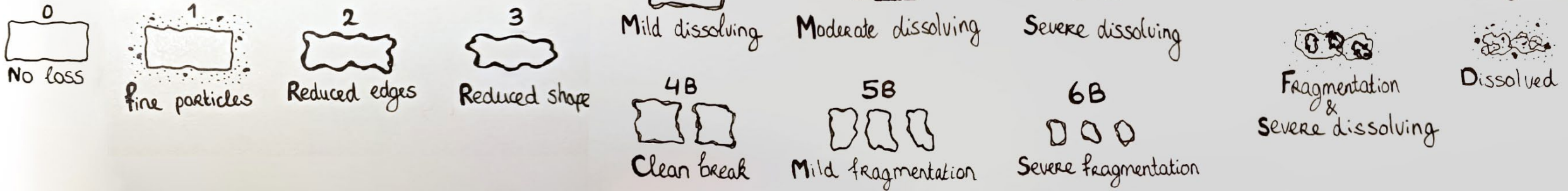
WETTING AND DRYING – RESULTS – ALBUMEN



WETTING AND DRYING – OBSERVATIONS

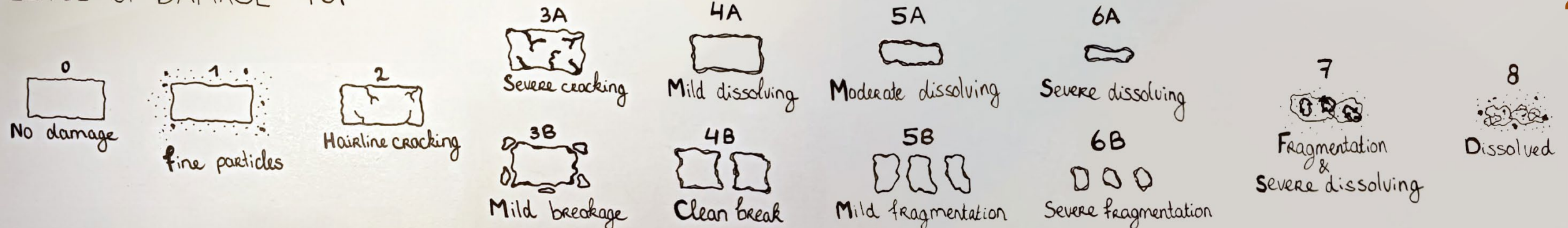
1

LEVEL OF MATERIAL LOSS - TOP

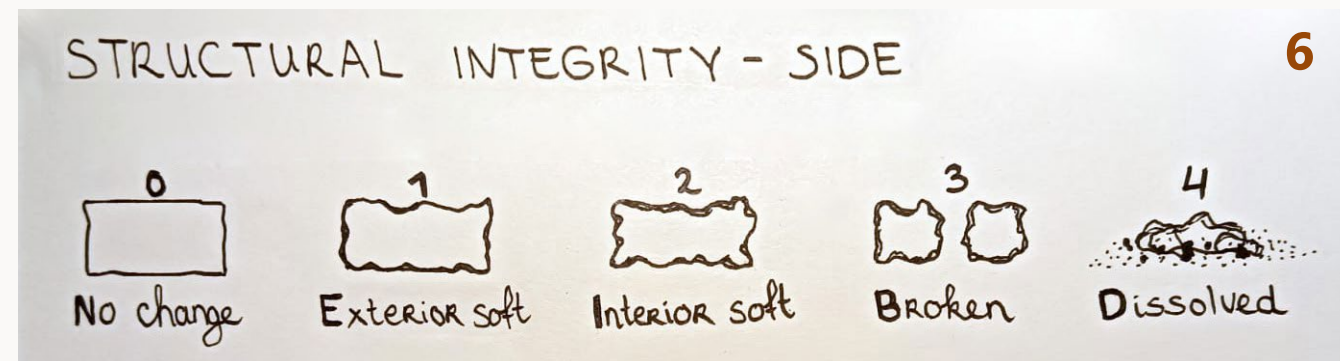
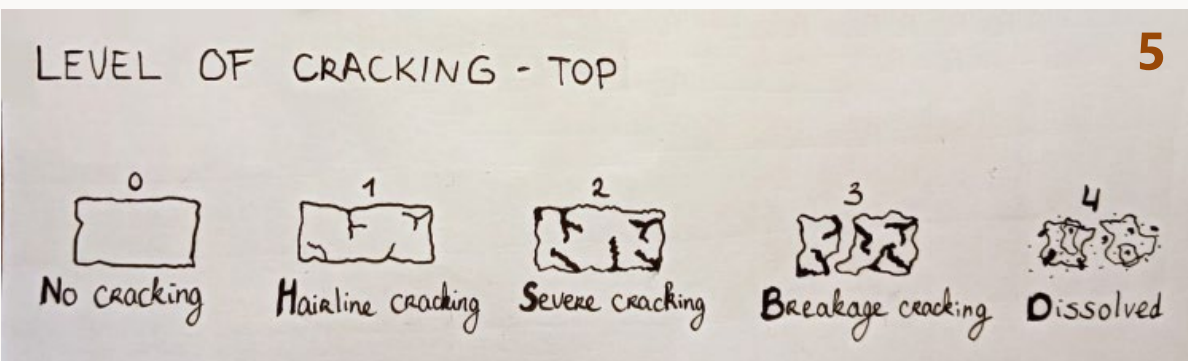
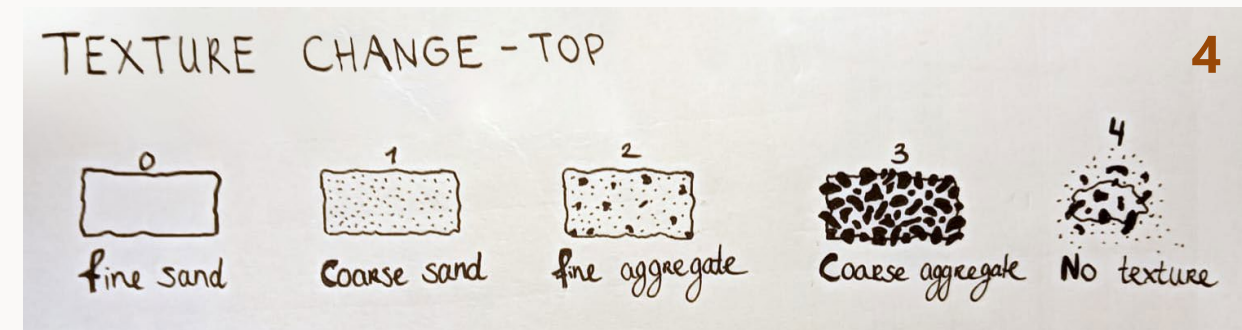
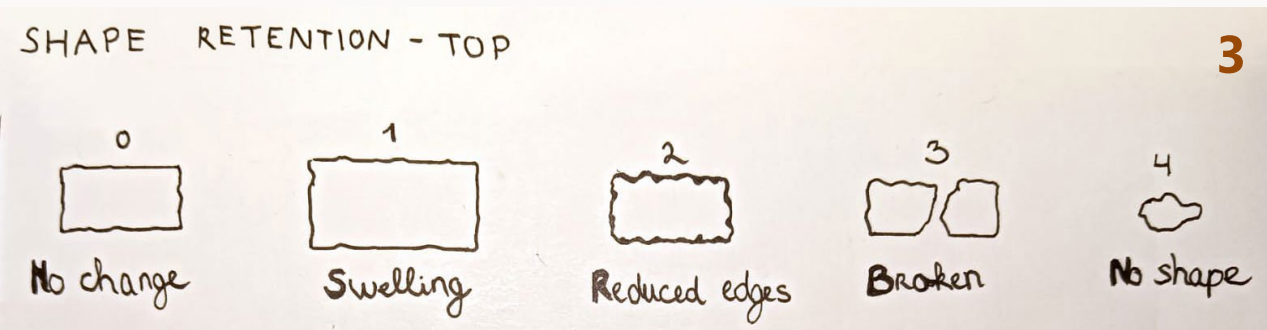


2

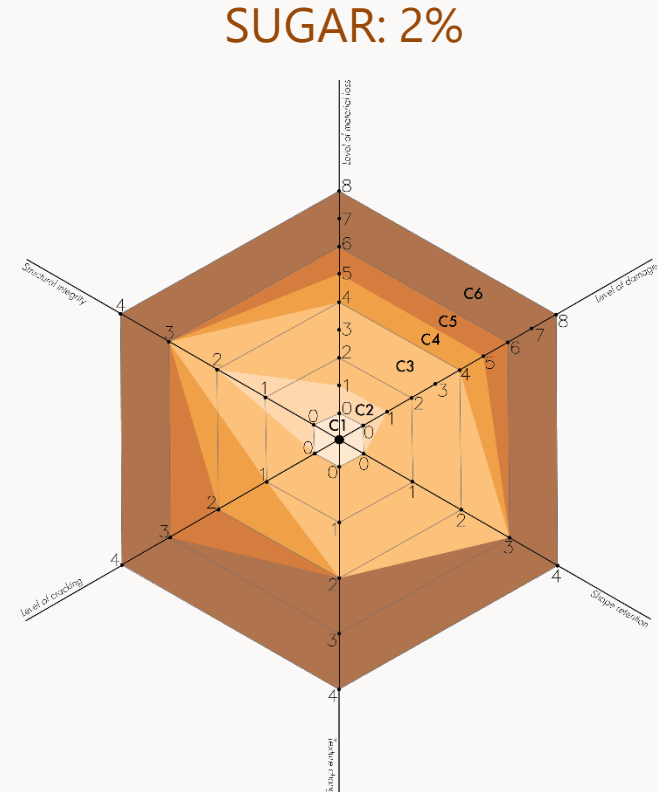
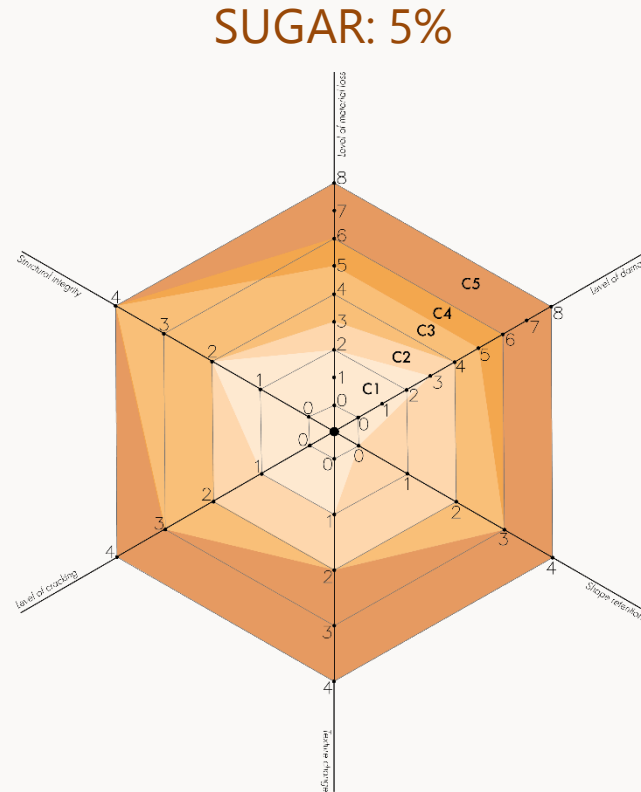
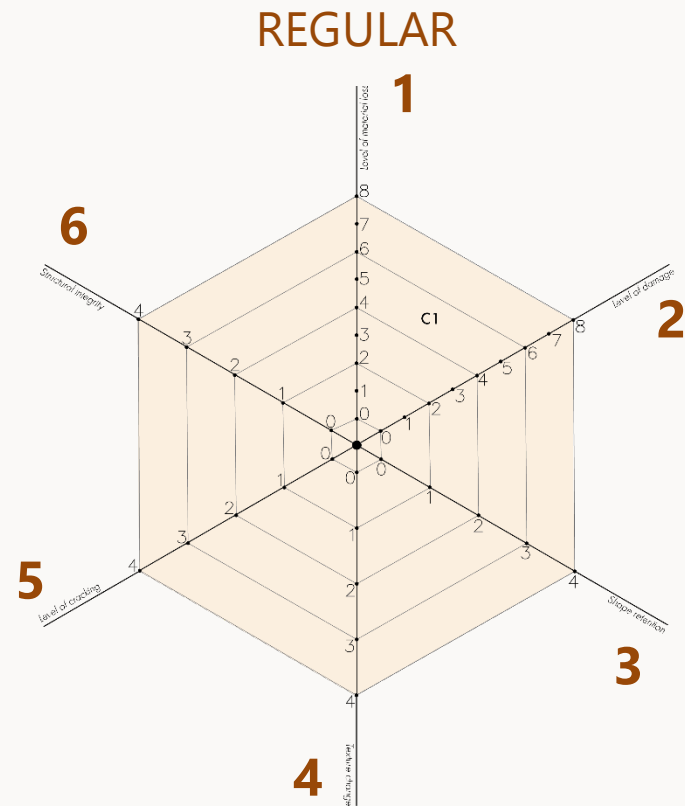
LEVEL OF DAMAGE - TOP



WETTING AND DRYING – OBSERVATIONS

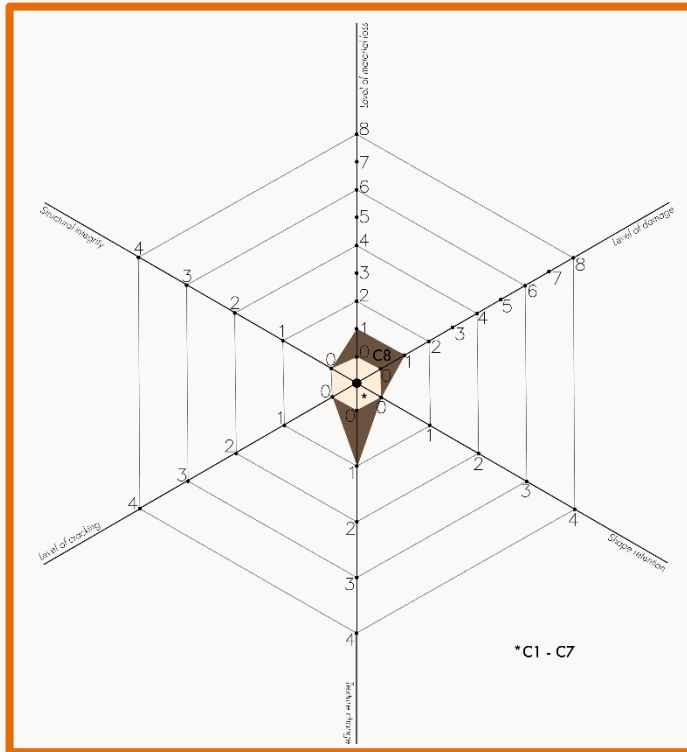


WETTING AND DRYING – OBSERVATIONS

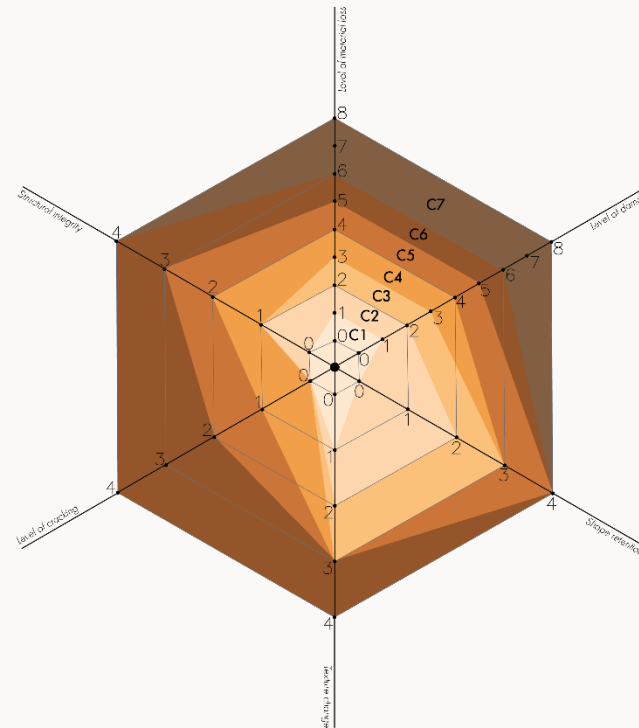


WETTING AND DRYING – OBSERVATIONS

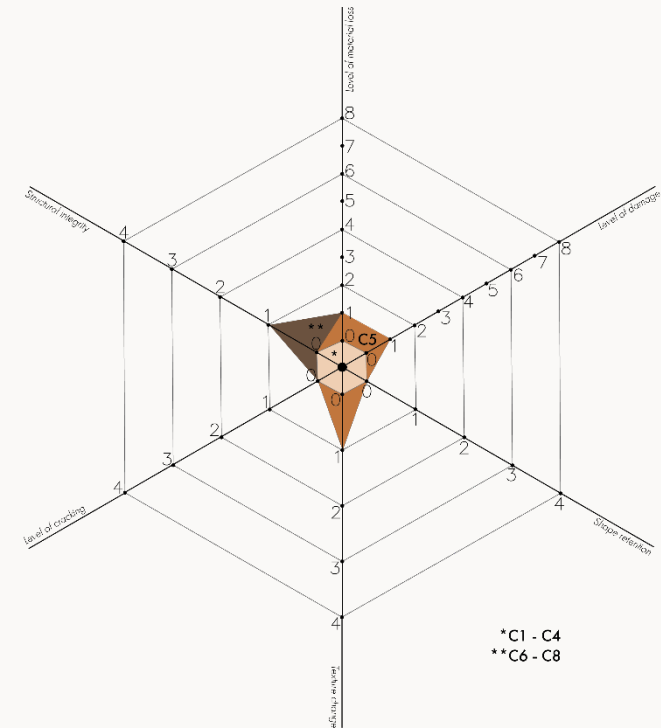
CEMENT



ALBUMEN: LIQUID

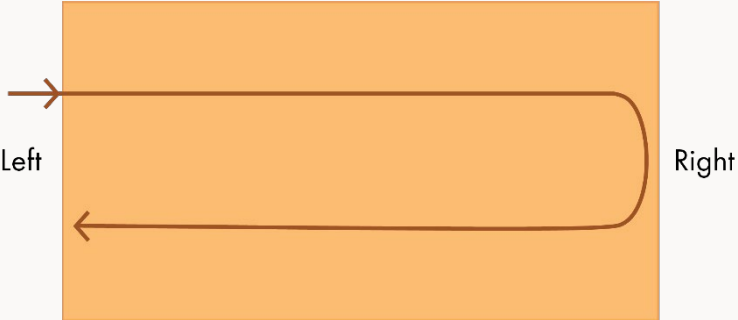
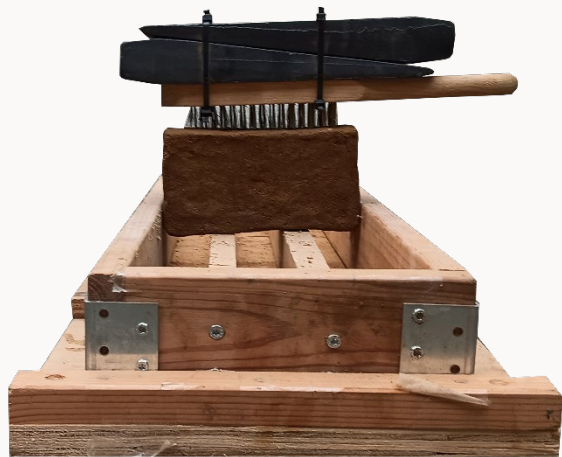


ALBUMEN: SOLID

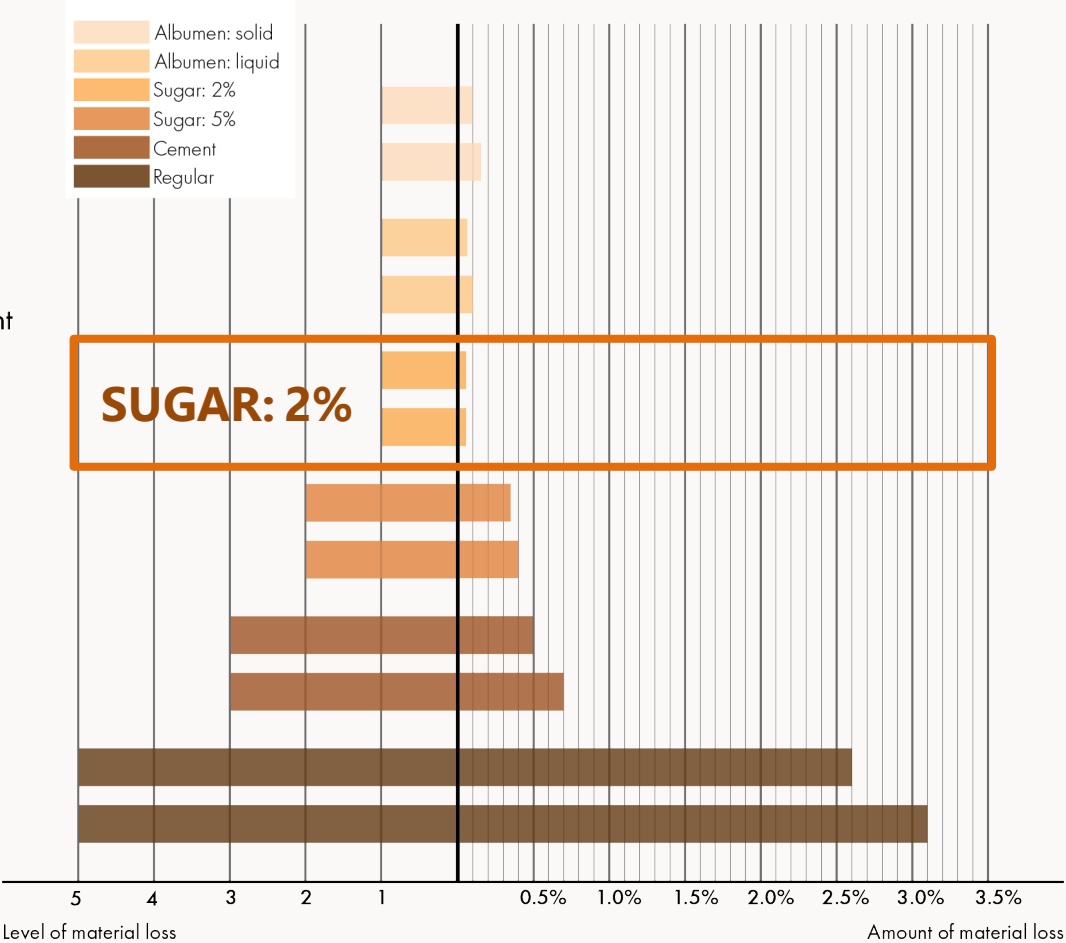


MECHANICAL – ABRASION

SET-UP



OBSERVATIONS



LEVEL OF MATERIAL LOSS



ABRASION - RESULTS

PRE-ABRASION

POST-ABRASION

REGULAR

CEMENT

SUGAR: 5%

SUGAR: 2%

ALBUMEN:
LIQUID

ALBUMEN:
SOLID



REGULAR

CEMENT

SUGAR: 5%

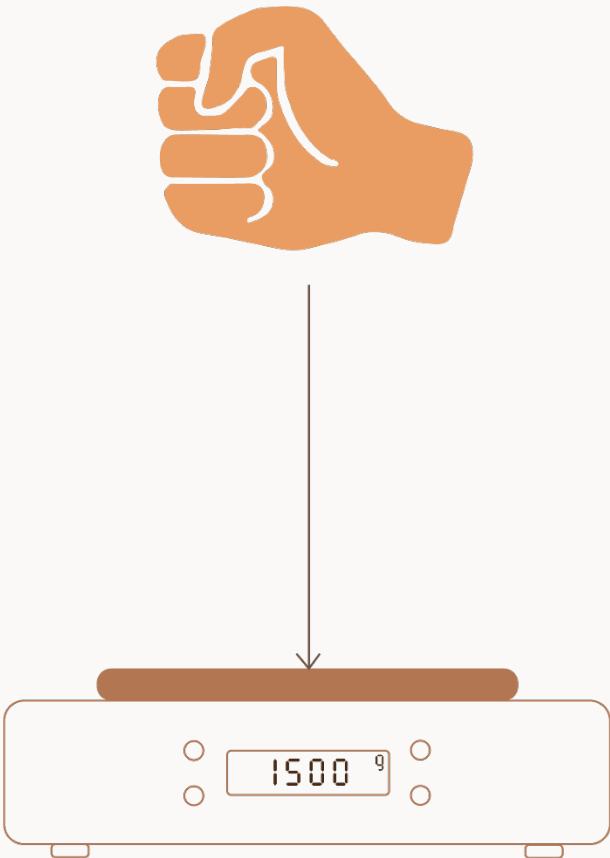
SUGAR: 2%

ALBUMEN:
LIQUID

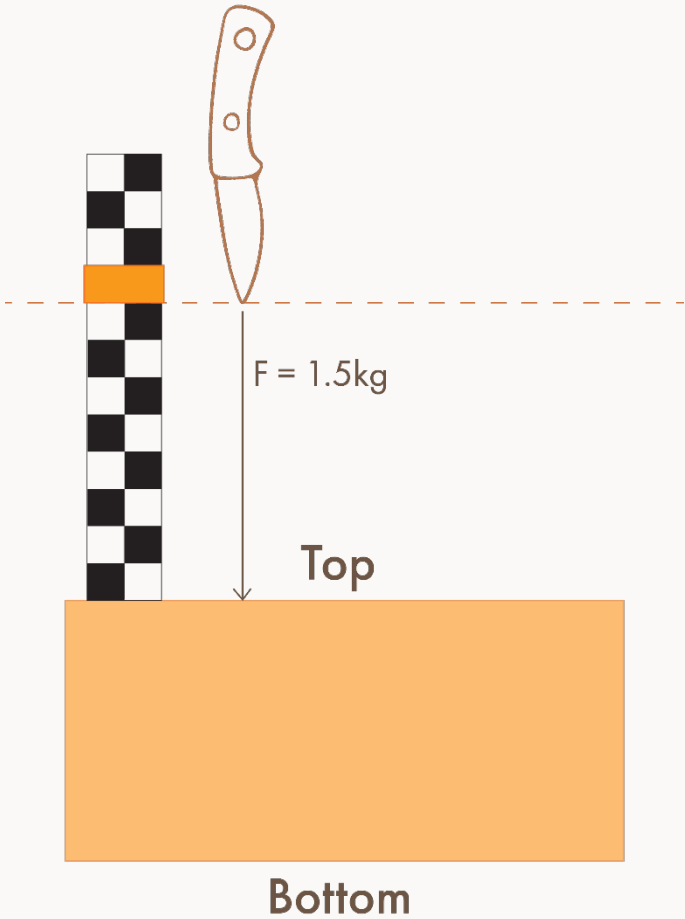
ALBUMEN:
SOLID

MECHANICAL – PENETRATION

IMPACT



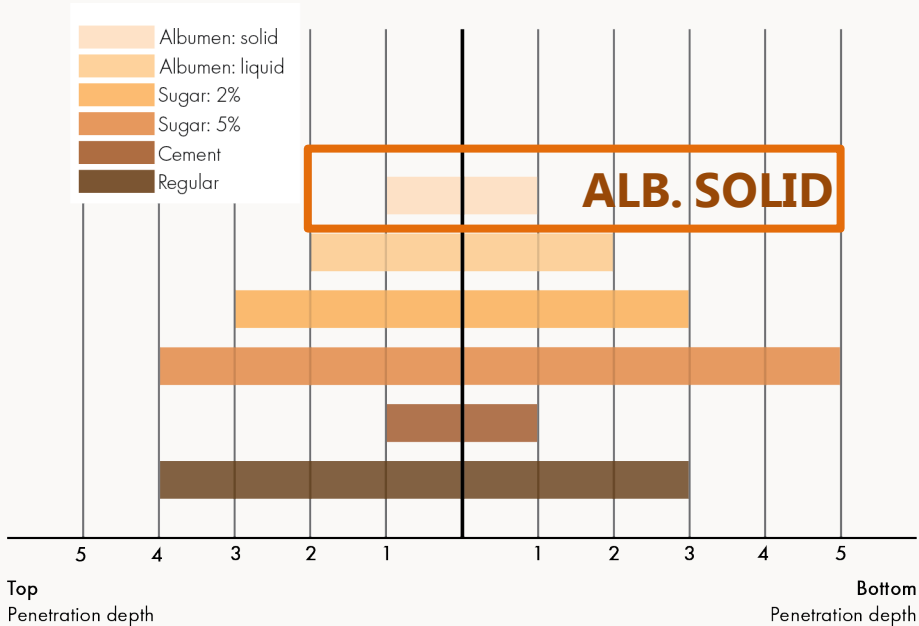
PENETRATION



DEPTH



OBSERVATIONS



PENETRATION – RESULTS

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

PENETRATION – RESULTS

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

PENETRATION – RESULTS

Albumen: Liquid



Top

Bottom

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

Albumen: Solid



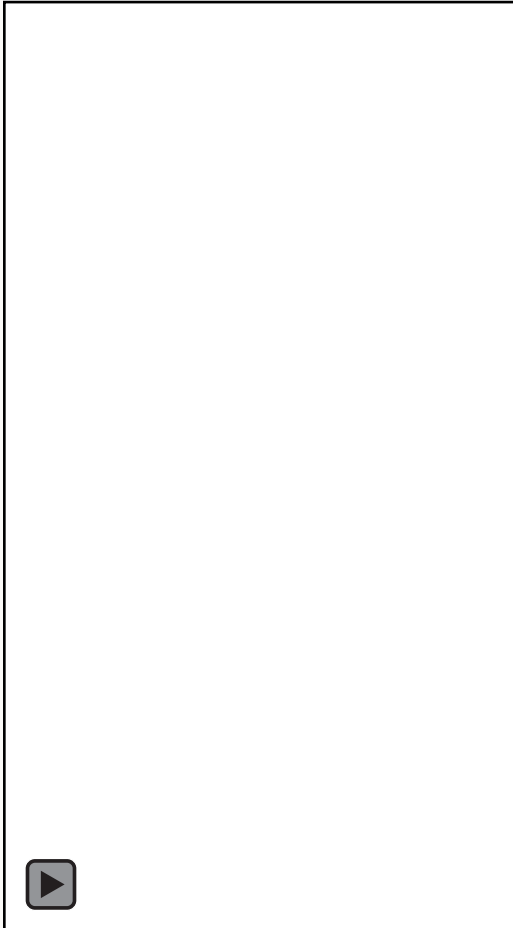
Top

Bottom

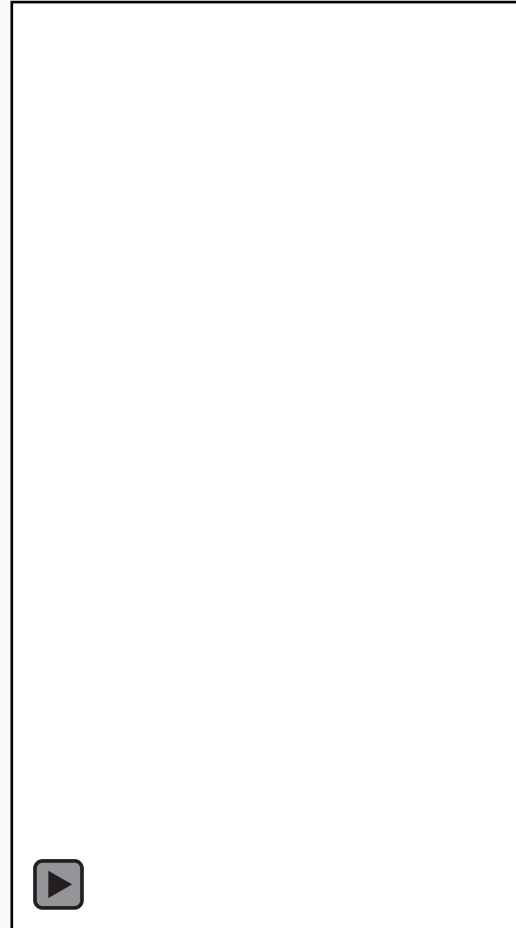
Albumen: solid	Penetration type	Damage type
Top	Clean cuts	Knife marks
Bottom	Clean cuts	Knife marks

MECHANICAL – STRENGTH TESTING

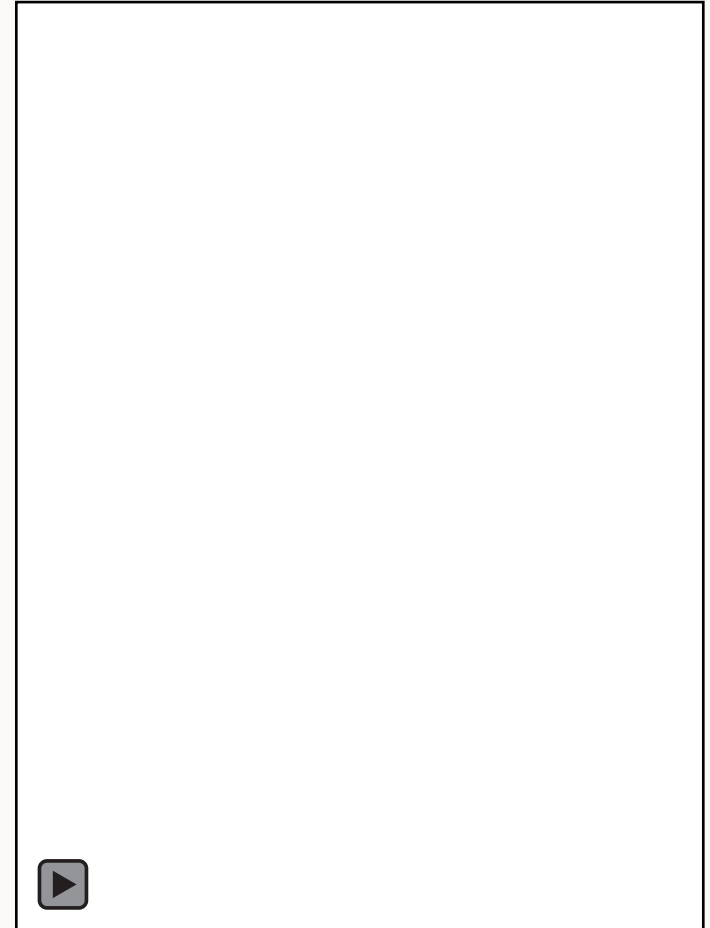
FLEXURAL STRENGTH



COMPRESSIVE STRENGTH



COMPRESSIVE STRENGTH 2.0



CONCLUSION – MECHANICAL TESTING

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

TESTING 3 – WEATHERING

11. Water erosion resistance - Drip test John Norton	12. Water erosion resistance - Spray test John Norton	13. Moisture absorption test John Norton	14. Freeze - thaw test Houben & Guillaud	15. Outside observation
- Form compressed earth brick sample group (CEB). - Let CEB completely dry in mould. - Place CEB on an engineered support board at an angle (45 degree). - Place large water container at an elevation above board (2.5m). - Acquire 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.	- Form compressed earth brick sample group (CEB). - Acquire 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/cm² (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 acquired 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 composition alteration or will require regular maintenance.	- 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.	- 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 absorbent 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 absorbent material between each round. - If test are to be interrupted, 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.	- 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. - Compare observations and test results to norms on weathering.
				

TESTING 3 – WEATHERING

11. Water erosion resistance - Drip test

John Norton

- Form compressed earth brick sample group (CEB).
 - Let CEB completely dry in mould.
 - Place CEB on an engineered support board at an angle (45 degree).
 - Place large water container at an elevation above board (2.5m).
 - Acquire cotton string with length 2.5x depth 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 - 12 hours
Material suitable for areas prolonged rain, over several hours.
 - Measured time = > 24 hours
Material suitable for areas persistent rainfall, one or more days.



12. Water erosion resistance - Spray test

John Norton

- Form compressed earth brick sample group (CEB).
 - Acquire 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/cm² (2 hours).
 - Observe results on CEB sample:
- Pitting = 5 - 12 mm
Material suitable for areas with short infrequent storms.
 - Pitting = 0 - 4 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 acquired 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 composition alteration or will require regular maintenance.



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 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 absorbent 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 absorbent material between each round.
- If test are to be interrupted, 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 direction.
- Return to location in 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.
- Compare observations and test results to norms on weathering.



WEATHERING – DRIP SET-UP

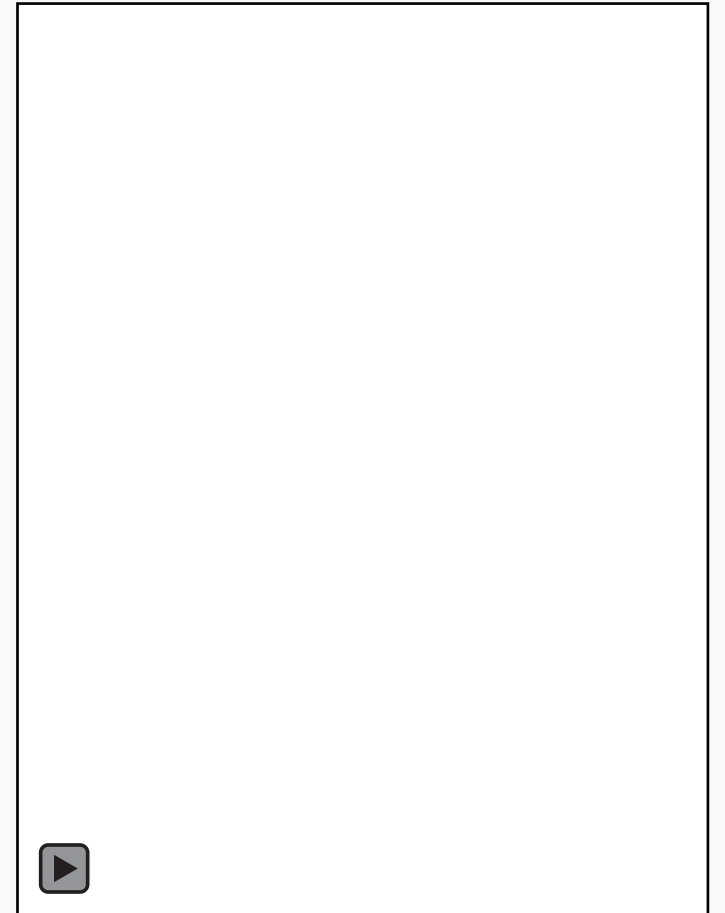
ATTEMPT 1



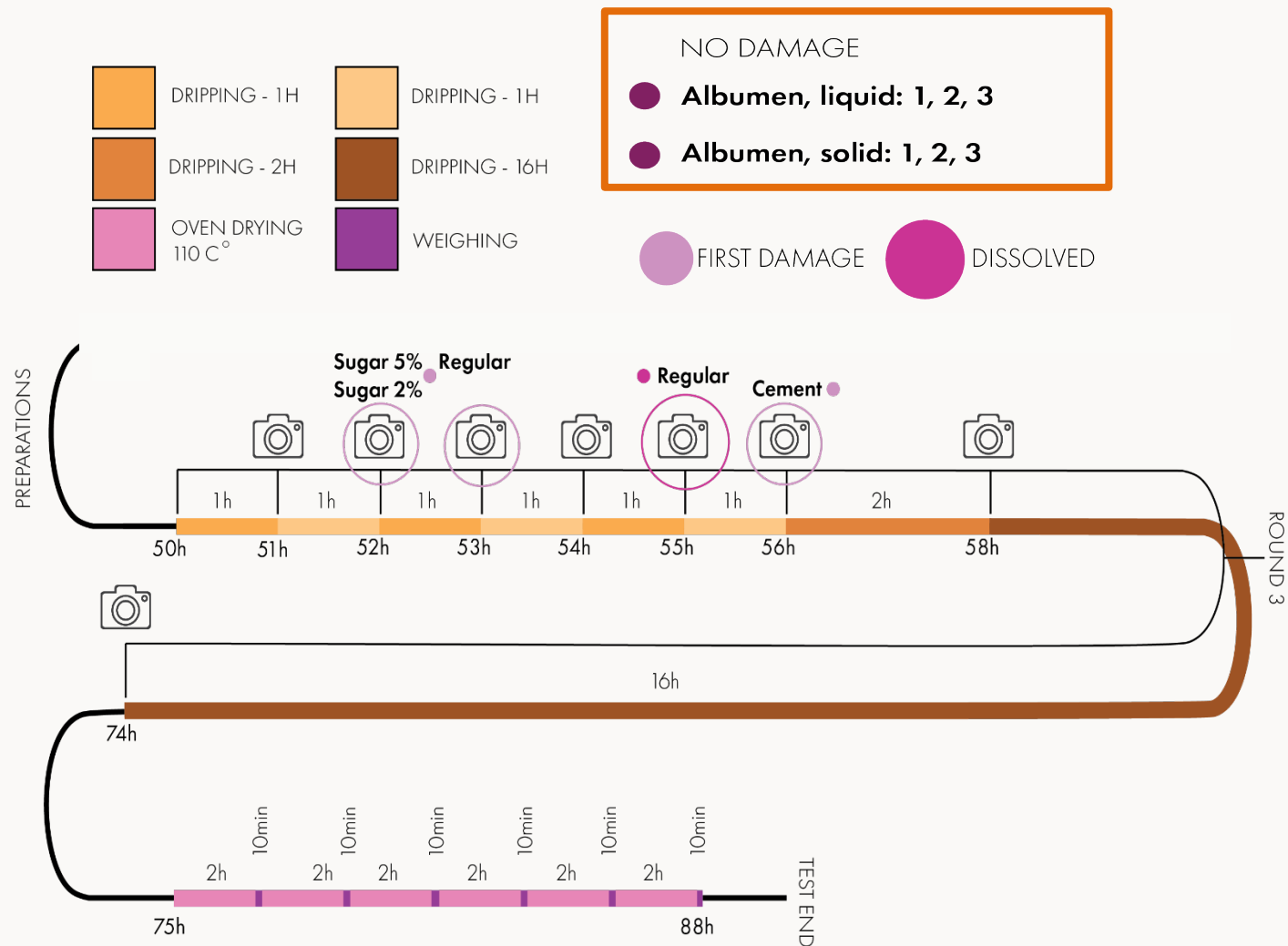
ATTEMPT 2



ATTEMPT 3



WEATHERING – DRIP



SET-UP



DRIP – RESULTS – REGULAR

ROUND 3



ROUND 1

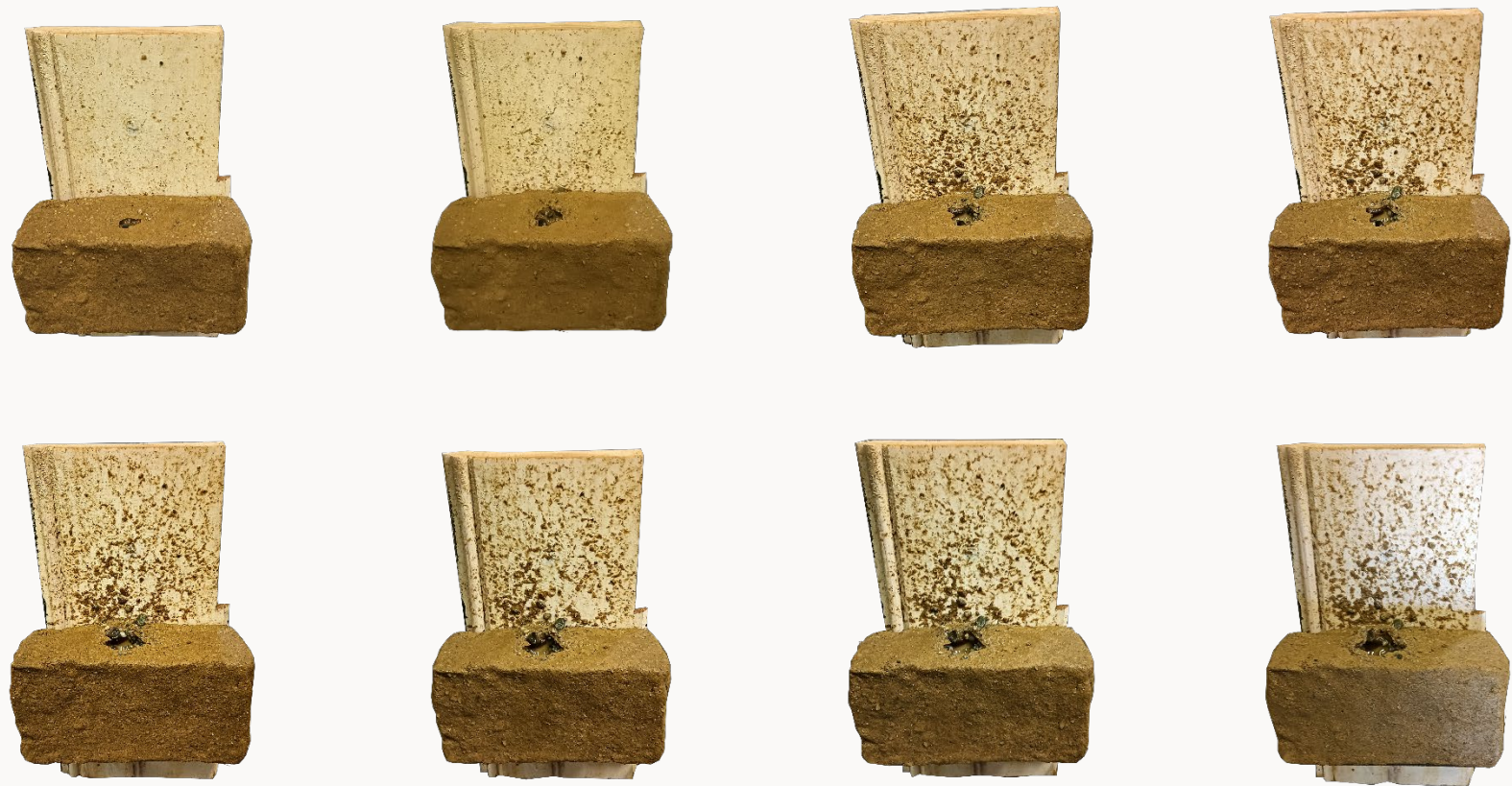


ROUND 2

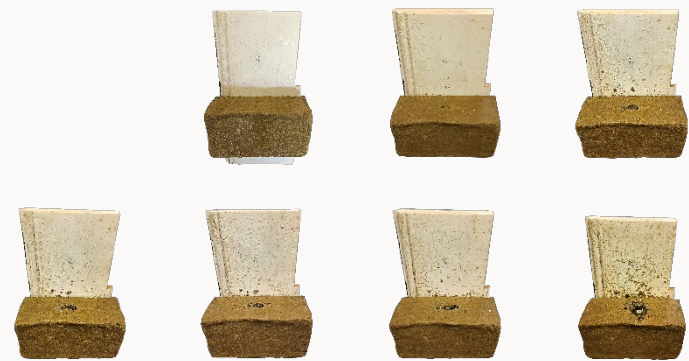


DRIP – RESULTS – SUGAR: 2%

ROUND 3



ROUND 1

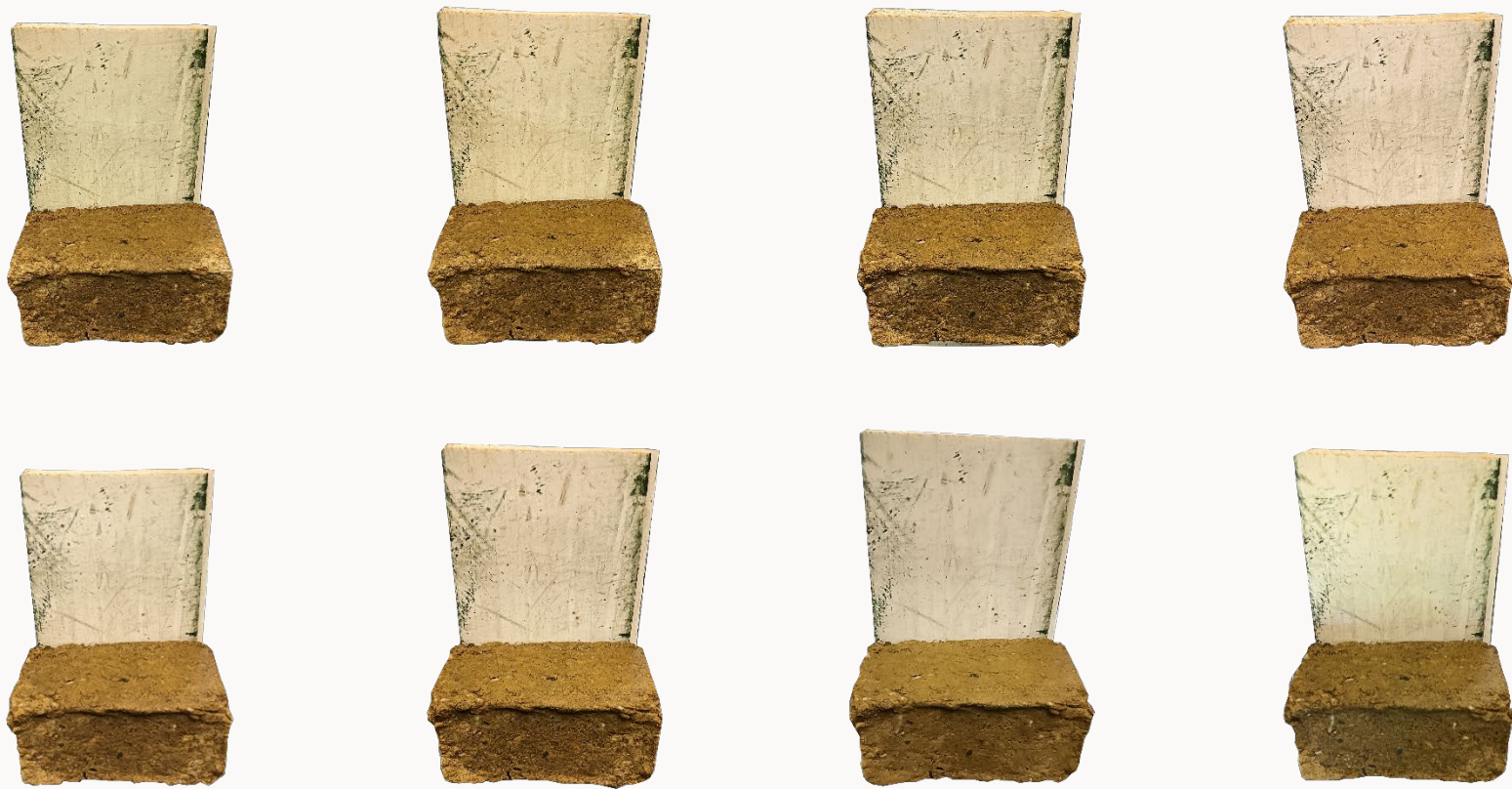


ROUND 2



DRIP – RESULTS – ALBUMEN: SOLID

ROUND 3



ROUND 1



ROUND 2



DRIP – RESULTS – POST-TESTING

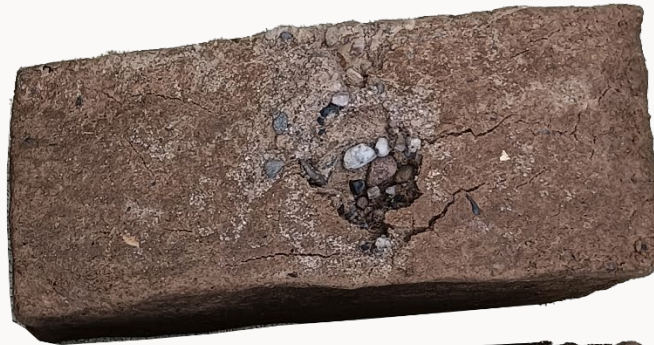
ROUND 2
SUGAR: 5%



ROUND 1
SUGAR: 5%



ROUND 3
SUGAR: 5%



ROUND 1
SUGAR: 2%



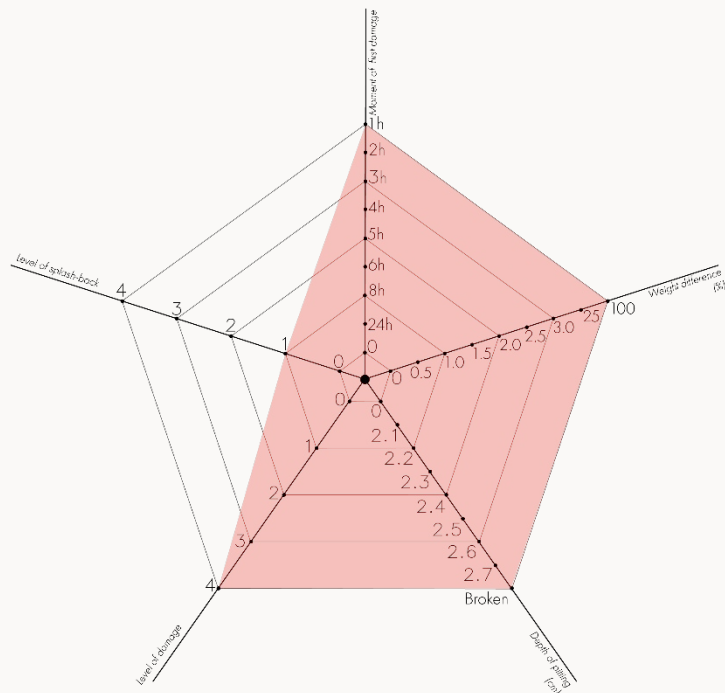
ROUND 3
SUGAR: 2%



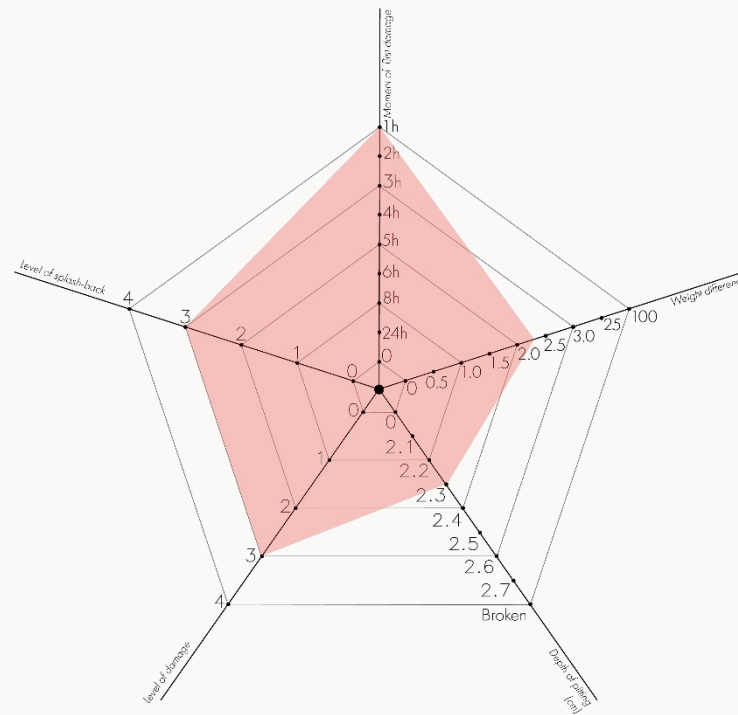
ROUND 2
SUGAR: 2%

DRIP – OBSERVATIONS

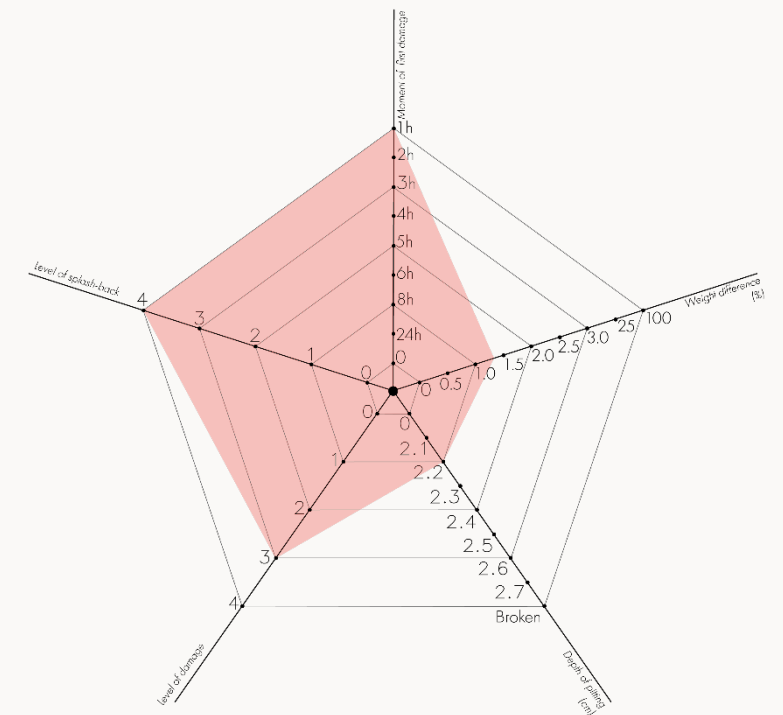
REGULAR



SUGAR: 5%

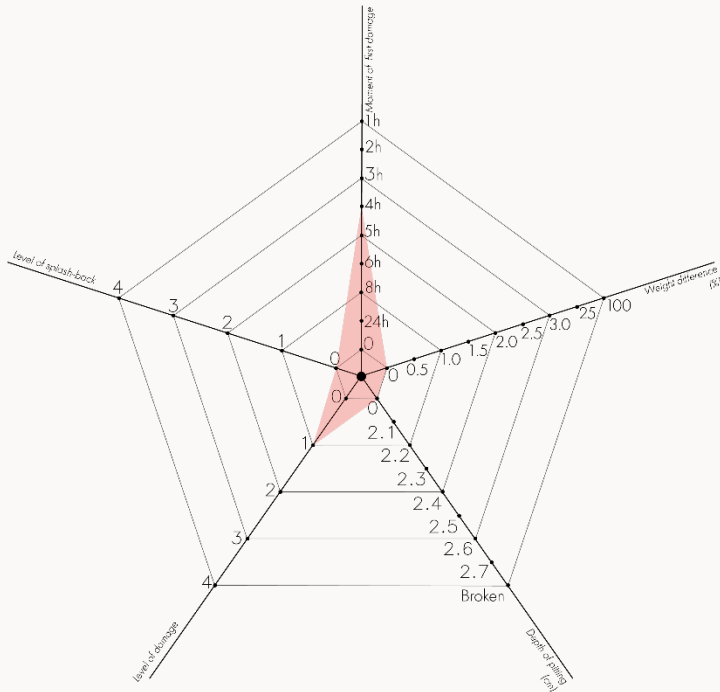


SUGAR: 2%

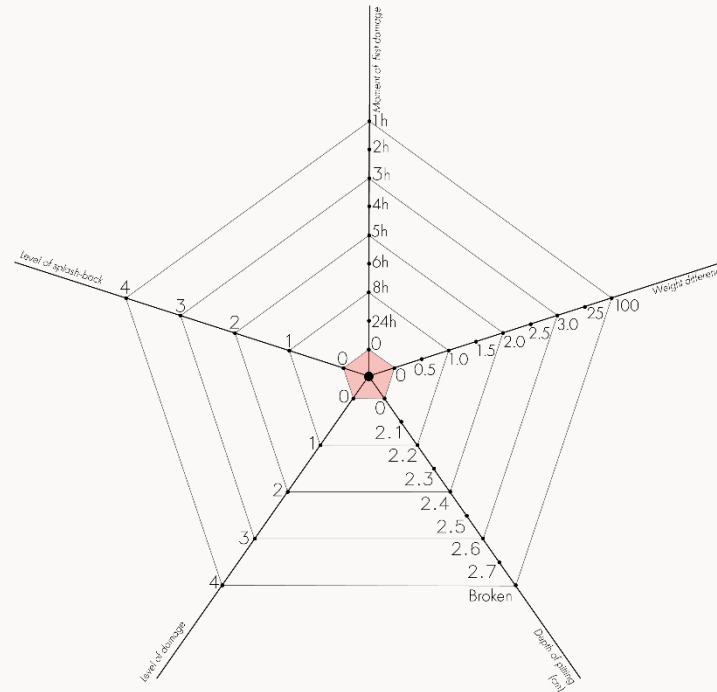


DRIP – OBSERVATIONS

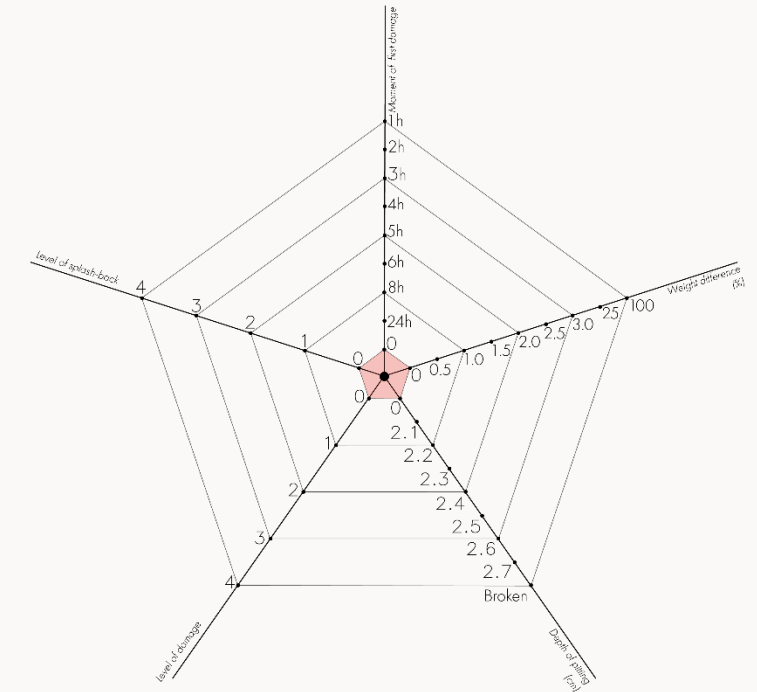
CEMENT



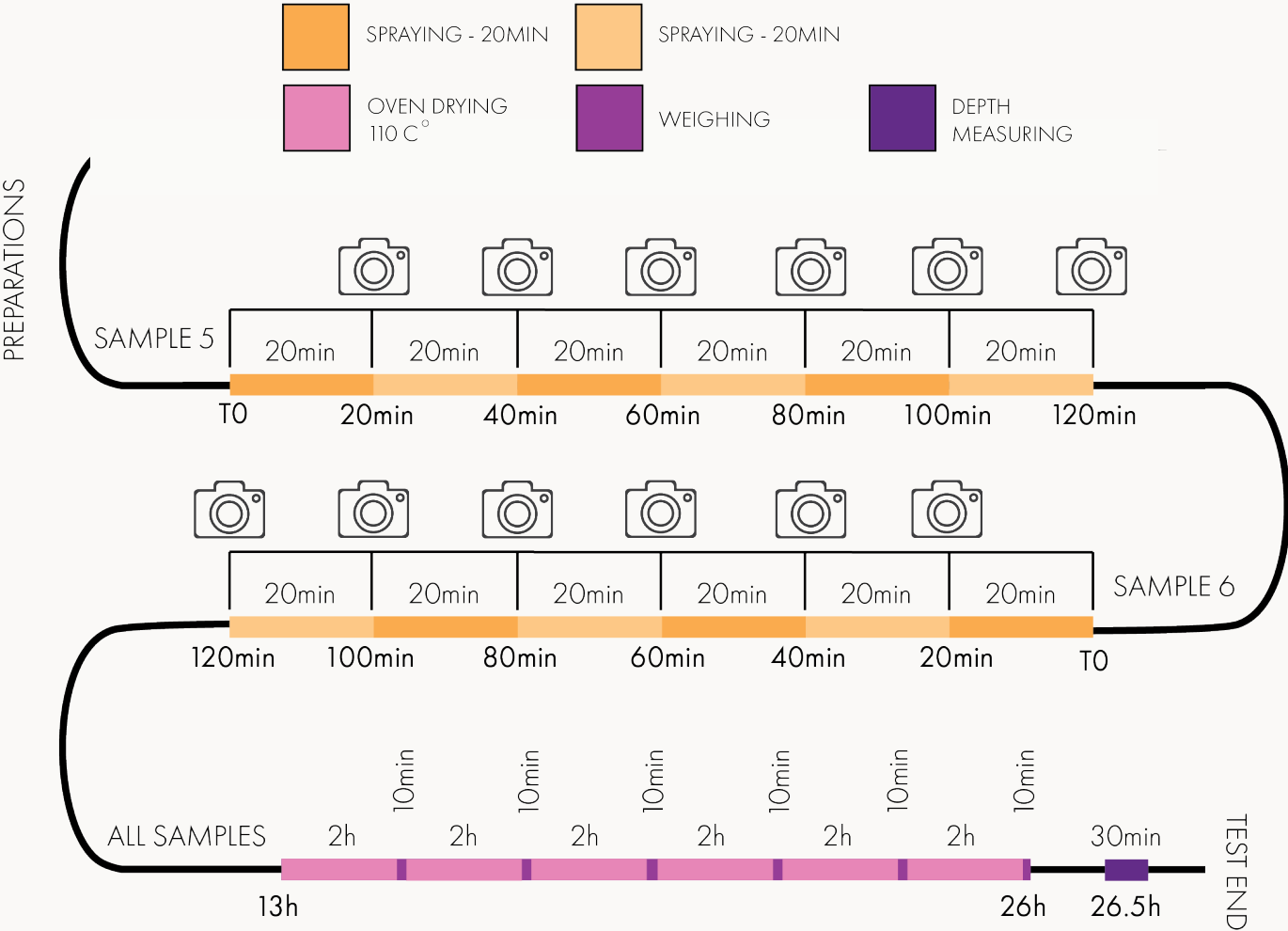
ALBUMEN: LIQUID



ALBUMEN: SOLID



WEATHERING – SPRAY



SET-UP



SPRAY – RESULTS

ROUND 2

REGULAR



SUGAR: 5%



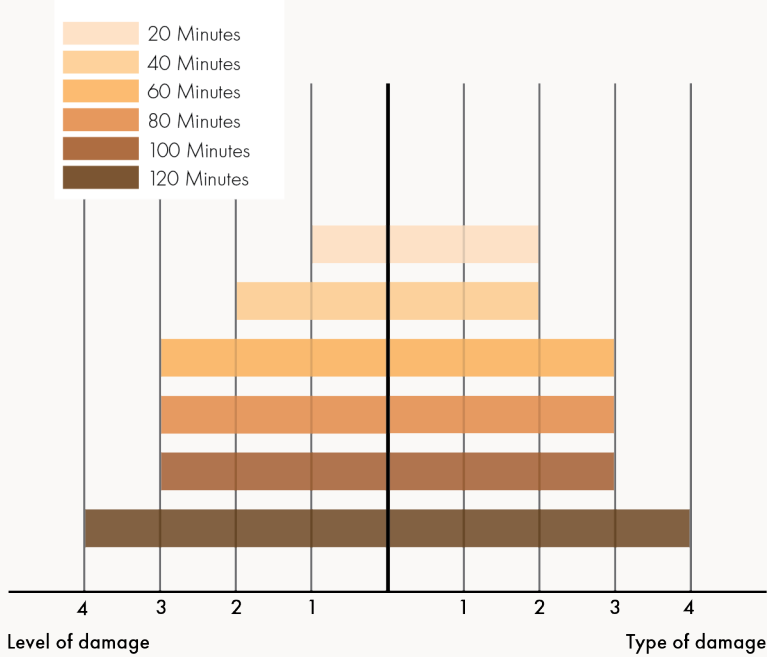
SUGAR: 2%



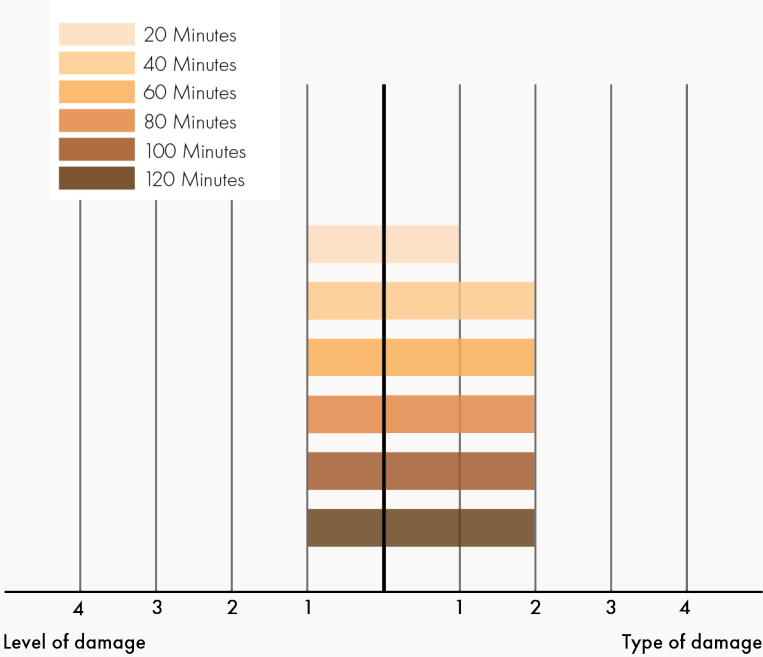
SPRAY – OBSERVATIONS

ROUND 2

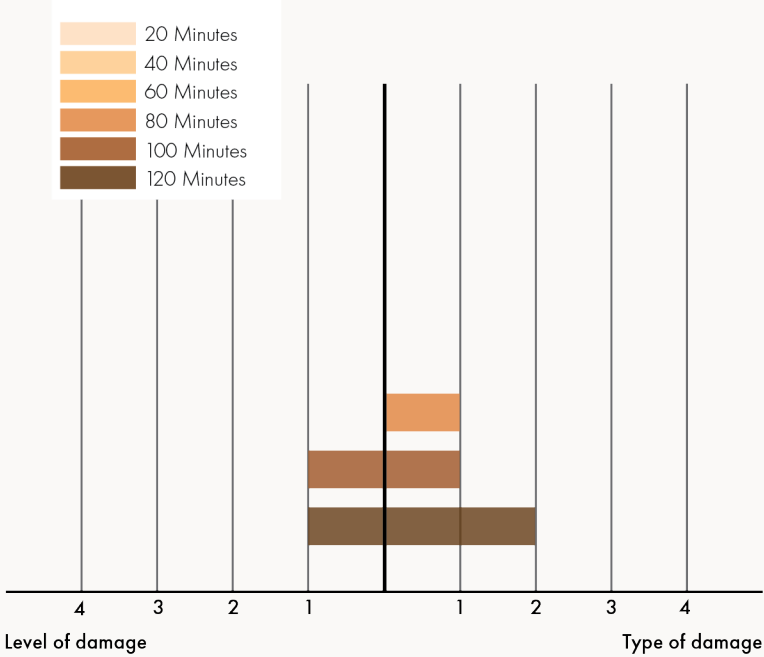
REGULAR



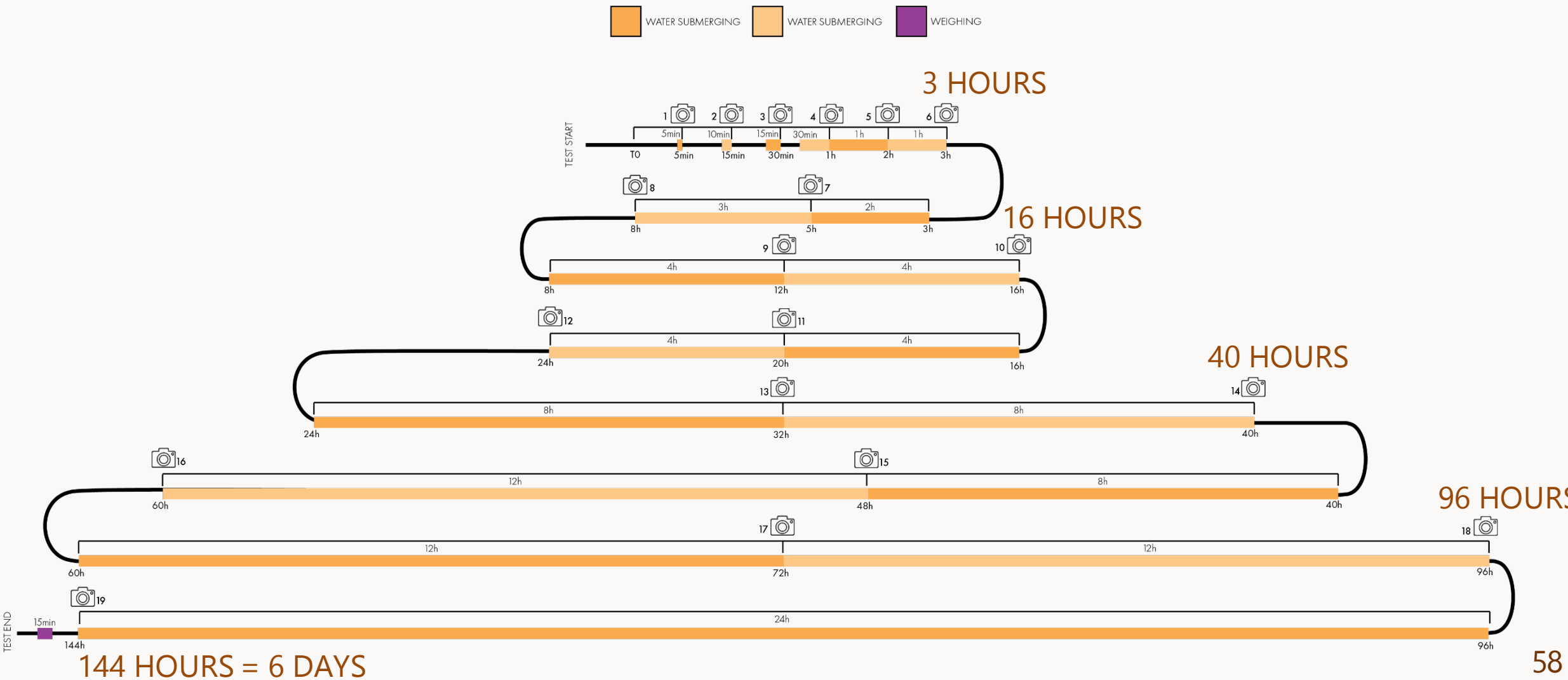
SUGAR: 5%



SUGAR: 2%



WEATHERING – MOISTURE ABSORPTION



MOISTURE ABSORPTION – RESULTS

1. 5 MINUTES



2. 15 MINUTES



FIRST DAMAGE



TOTAL DAMAGE

3. 30 MINUTES



4. 1 HOUR



MOISTURE ABSORPTION – RESULTS

5. 2 HOURS



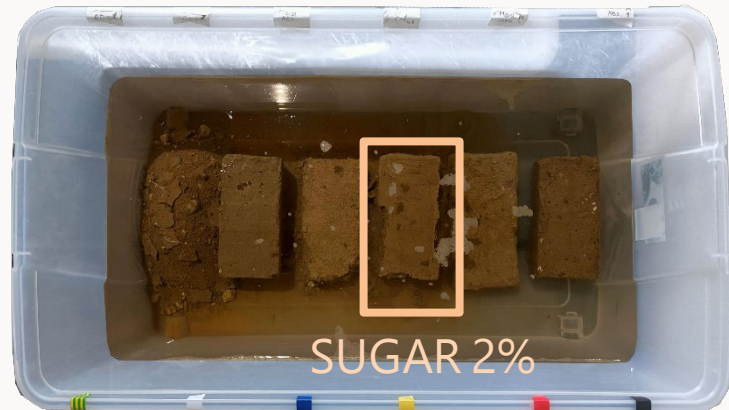
6. 3 HOURS



7. 5 HOURS



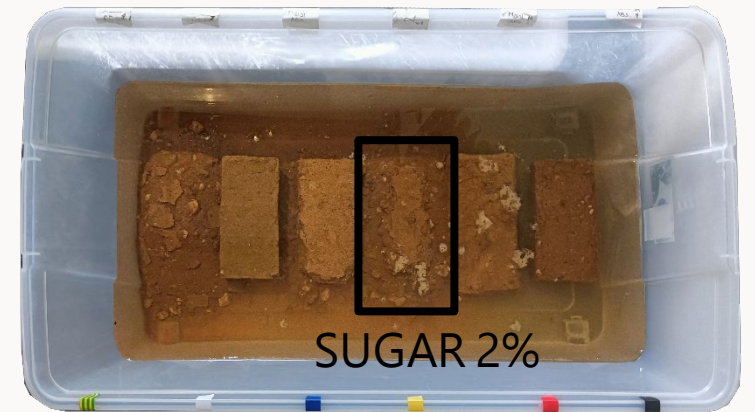
8. 8 HOURS



9. 12 HOURS



10. 16 HOURS



MOISTURE ABSORPTION – RESULTS

11. 20 HOURS



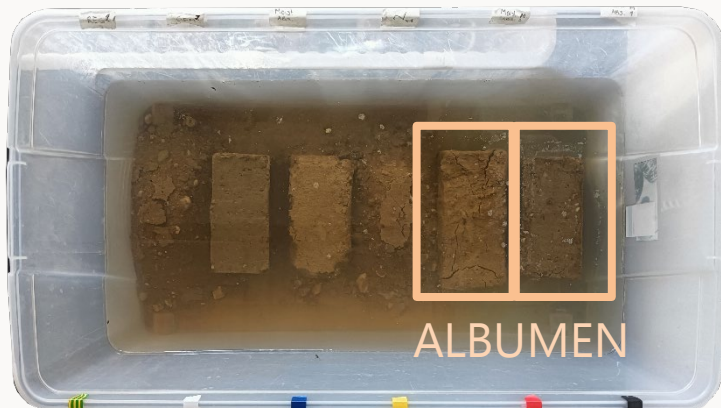
12. 24 HOURS



13. 32 HOURS



14. 40 HOURS



15. 48 HOURS



16. 60 HOURS

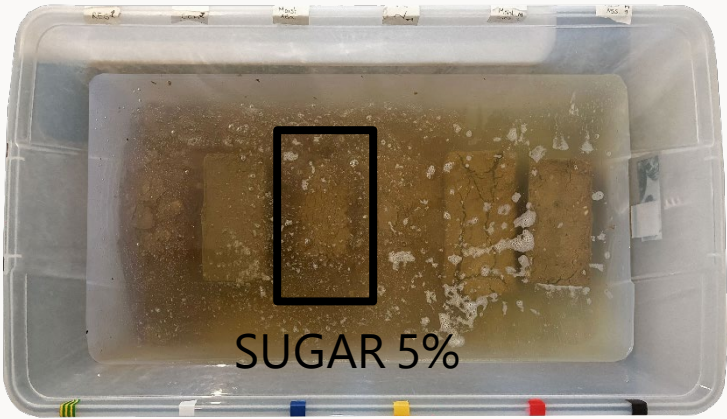


MOISTURE ABSORPTION – RESULTS

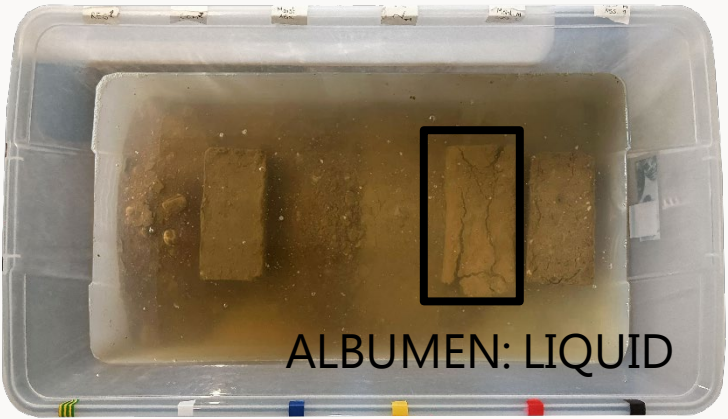
17. 72 HOURS



18. 96 HOURS



19. 144 HOURS



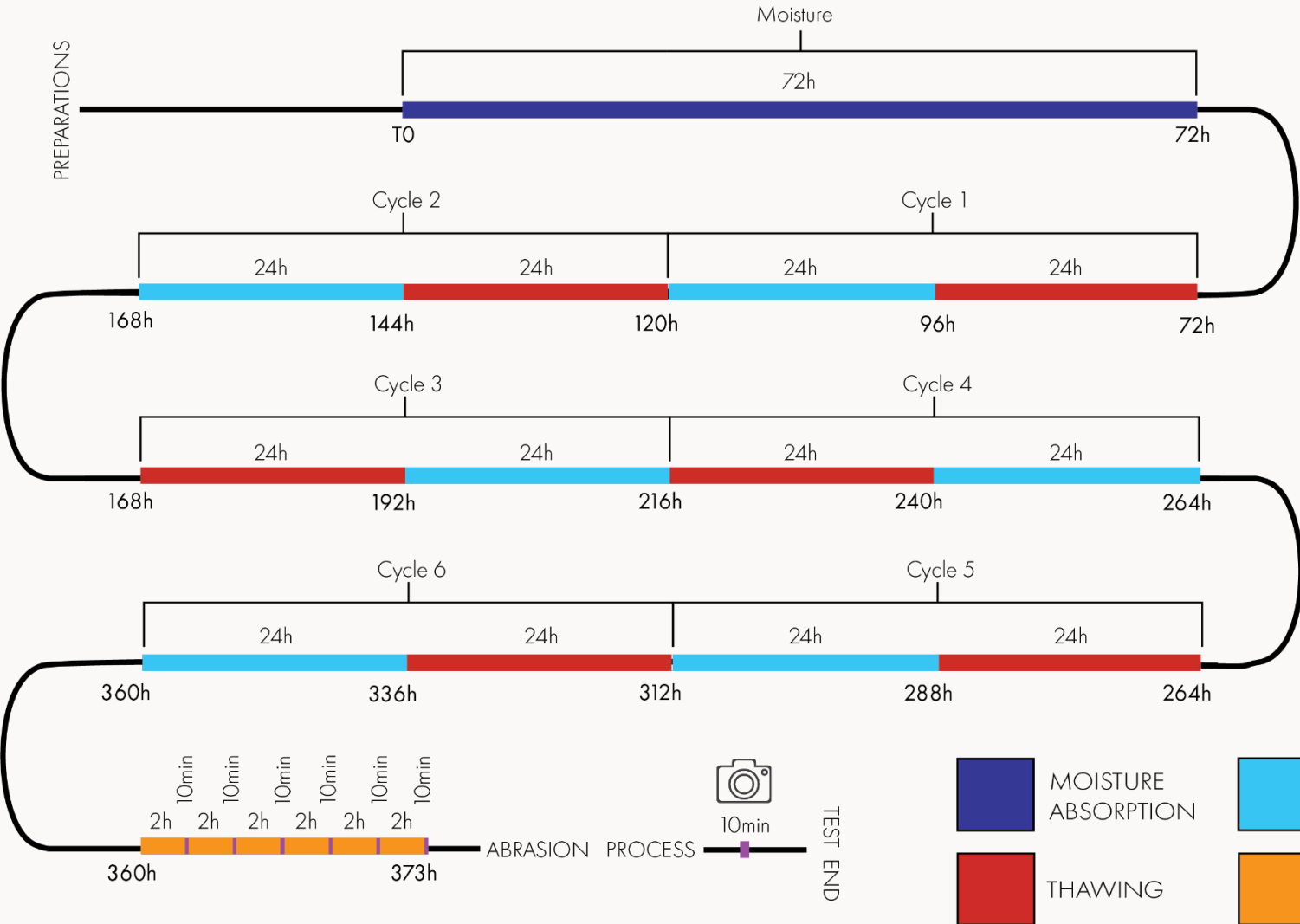
FIRST DAMAGE

Regular	5 minutes
Cement	12 hours
Sugar: 5%	2 hours
Sugar: 2%	5 hours
Albumen: Liquid	40 hours
Albumen: Solid	40 hours

TOTAL DAMAGE

Regular	1 hour
Cement	-
Sugar: 5%	96 hours
Sugar: 2%	16 hours
Albumen: Liquid	144 hours
Albumen: Solid	-

WEATHERING – FREEZE AND THAW



SET-UP



FREEZE AND THAW – RESULTS

REGULAR – NO ABRASSION



REGULAR – ABRASSION



FREEZE AND THAW – RESULTS

CEMENT



SUGAR: 5%



FREEZE AND THAW – RESULTS

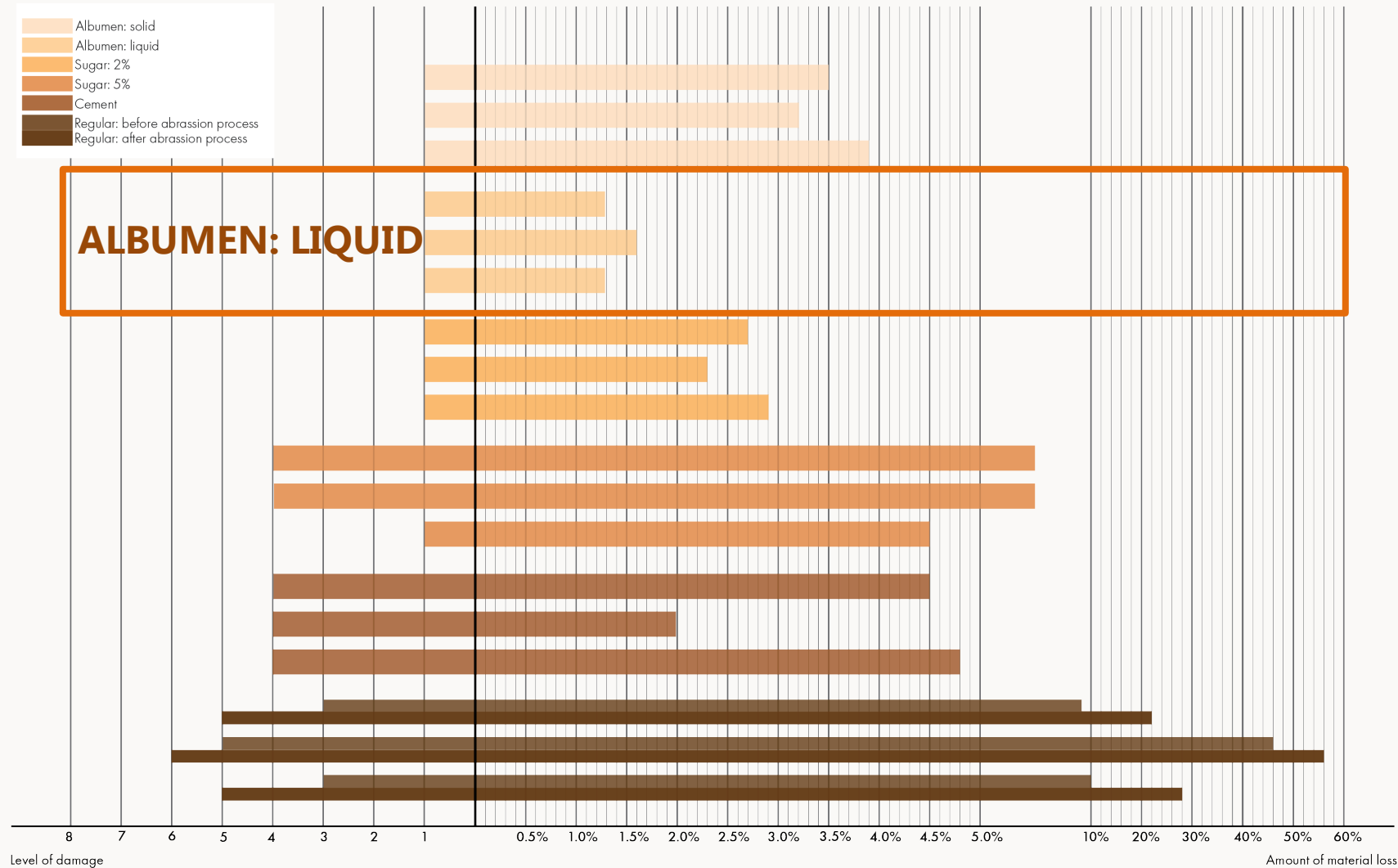
ALBUMEN: LIQUID



ALBUMEN: SOLID



FREEZE AND THAW – OBSERVATIONS



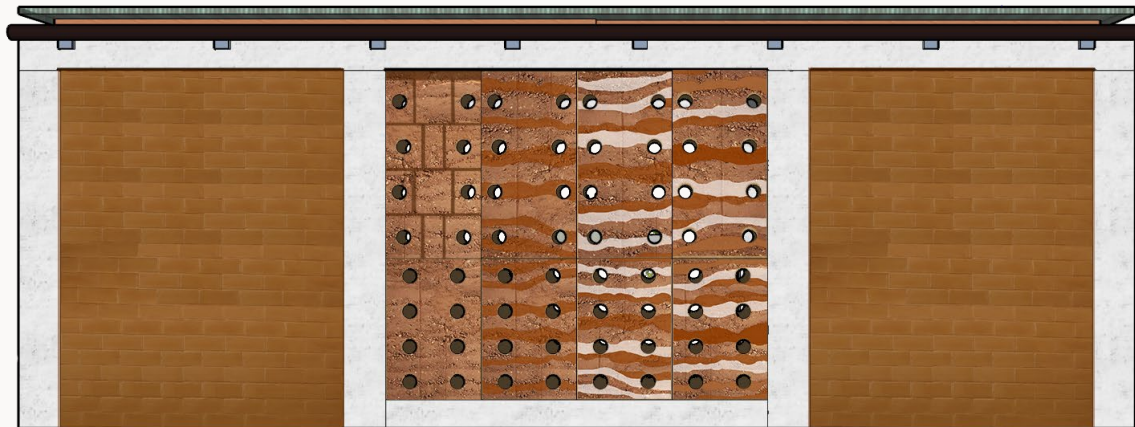
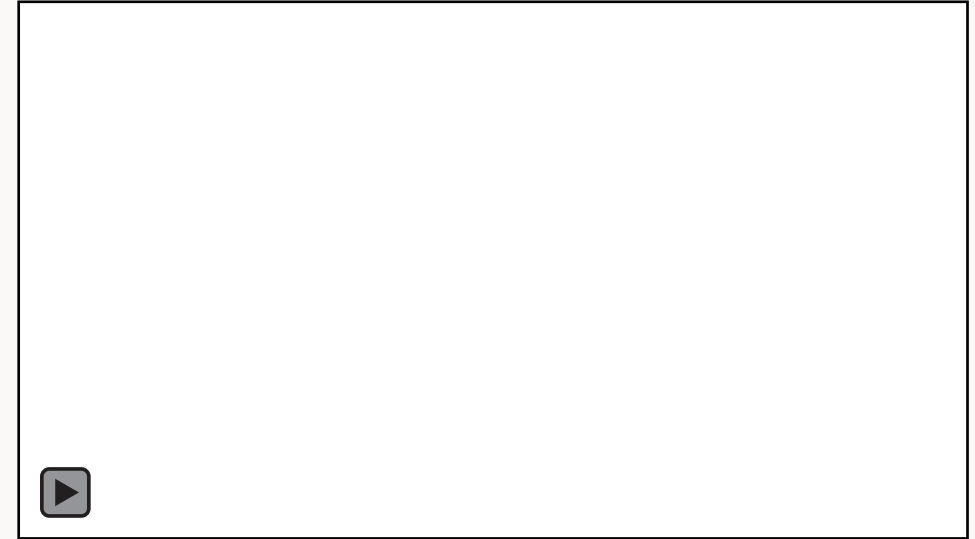
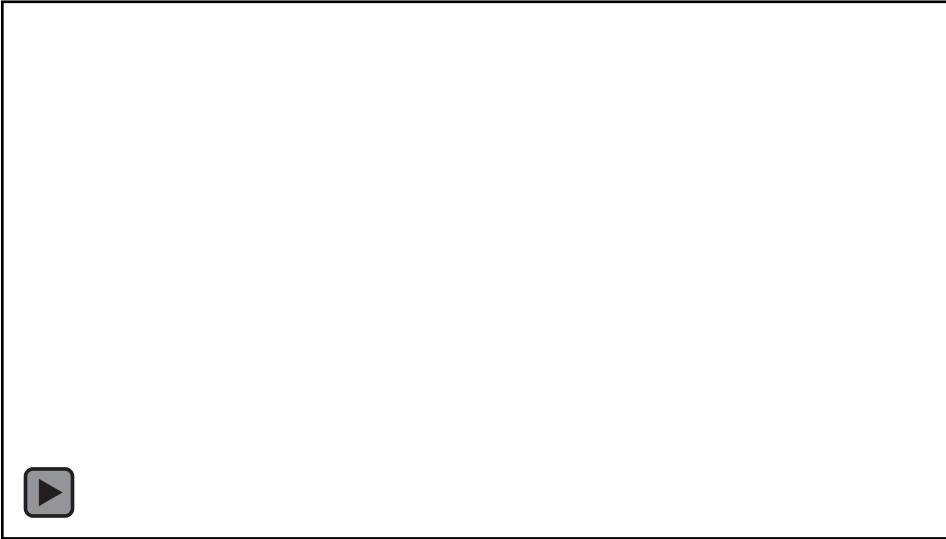
CONCLUSION – TESTING TOTAL

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	5 th
Cement	2	1	1	4	8	18	3 rd
Sugar: 5%	4	3	4	5	16	31	4 th
Sugar: 2%	3	2	4	2	11	18	3 rd
Albumen: liquid	1	1	3	1	6	14	2 nd
Albumen: solid	1	1	2	3	7	13	1 st

DEHYDRATED ALBUMEN



FURTHER RESEARCH



MAIN QUESTION

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

"The only difference between screwing around and science is writing it down"

– Adam Savage, MythBusters