Agristone

Optimizing CorNcrete: Enhancing structural and aesthetic performance for architectural applications

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Abstract

Concrete is the world's second most used material after water. Its binder, cement, produces about 8% of global carbon emissions and accounts for 90% of concrete's footprint. Reducing this impact is key to meeting the Paris Agreement's 2030 and 2050 targets, especially in the Netherlands where low-emission housing solutions are urgently needed. Previous work on CoRncrete, a cornstarch-based concrete, demonstrated the potential of cement-free binders but was limited by poor water resistance.

This research builds on that foundation through a four-phase Material Driven Design approach. Context and material research included bench-marking, interviews, and desk study. In the tinkering phase, recipe adjustments, sealers, and surface treatments were explored, with preliminary submersion tests leading to a revised process of wet pressing and post-curing (minimizing manufacture steps), and the addition of eggshell powder as partial sand replacement. Technical characterization then tested mixes with 7.5%, 10%, and 12.5% sand replacement with eggshell powder under varied curing times, climates (5 °C/60% RH, 30 °C/60% RH, 30 °C/80% RH), and submersion conditions, using triplicate samples. Results showed a improvement in water resistance: all recipes withstood at least 24 hours of immersion compared to 10 minutes for the original mix, while the 12.5% eggshell variant achieved the highest compressive strength (14 MPa after 21 days). Experiential characterization with nine participants found a preference for eggshell-based samples, with plain, marbled, and pigmented finishes each valued for different architectural applications, as assessed with the MDD toolkit.

The final material, named Agristone, is produced as a pre-cast block (300 × 100 × 200 mm), aligning with standard concrete block dimensions for straightforward adoption in low-rise inner-leaf or partition walls. With a compressive strength of 14 MPa, Agristone falls within the range of structural lightweight concrete (11.8–21 MPa) (Ansys Granta Edupack), ensuring its technical viability. It is available in a palette of natural oxide colors, reducing finishing needs and adding design flexibility. Life cycle comparisons indicate ~45% lower CO_2 eq emissions and 60% lower embodied energy than conventional lightweight concrete. Costs of Agristone are estimated to be higher than concrete blocks (€1.55/block vs. €0.89/block), but these may be offset by the material's sustainability, reduced construction steps, and aesthetic added value.

This work demonstrates that a cornstarch-based concrete with eggshell additive and simplified manufacture method can achieve both structural performance and moisture resistance, establishing Agristone as a promising step toward bio-based, cement-free construction materials.



Preface

This thesis concludes my master's studies in Integrated Product Design. Over the past year I followed courses in Building Technology at the Faculty of Architecture, fulfilling my interest in design for the build environment. Developing new materials has long been a personal interest, and this project offered the opportunity to connect that passion with the building sector while preparing for a future career in sustainable construction.

The work is aimed at architects, engineers, and researchers who wish to explore alternatives to conventional concrete and contribute to large-scale sustainability in the built environment.

I would like to thank all those who supported me throughout this research. Professionals from architecture, engineering, materials science, and LCA specialists shared their knowledge and enthusiasm, helping to move the project to the next level. I am grateful to the participants in the user sessions for their enthusiasm, as well as to friends and family for their encouragement and practical help, in particular Misha Ruijgrok and Marijn Leeuwenberg for their assistance with technical challenges. My appreciation also goes to the staff of Applied Labs for their guidance and resources, and to Ton Riemslag and Raymond Dekker from the Mechanical Engineering Materials Laboratory for their help with the technical tests done in this research.

Finally, I am deeply thankful to my supervisors, Sepideh Ghodrat and Silje Dehli, whose expertise and support have been invaluable to both my technical and professional growth. You both showed consistent enthusiasm for my project and gave me the courage I needed to get through rough periods. I look up to you both and feel very proud to be able to graduate next to you. I wish you both the best and hopefully we will cross each others paths again.

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Introduction 1

Introduction
Literature research

Need for concrete
From the industrial revolution until today, we have been using new carbon intensive materials like masonry, steel and concrete to build more efficient and higher buildings (Churkina et al., 2020). In this revolution, improved production processes increased job opportunities which made people move to cities (Lewis, z.d.). The re-invention of concrete, Portland cement, happened also during this time, being the closest to the concrete we use today (Megaslab, 2024). Since the industrial revolution, urbanization has increased even further. More than 50% of the world population currently lives in urban areas compared to 34% in 1960 (World Bank Open Data, z.d.). With the rise in urbanization, it is estimated that concrete use will rise even more (Cheng et al., 2023). To accommodate for the lack of space for these dens populations and to leave room for infrastructure and leisure, building vertically with high-rise buildings is often chosen (Vuran, z.d.)(Insider, 2024). Not only for infrastructure needs, but also for creating high-rise buildings, concrete serves as the most promising solution due to its many great mechanical properties, durability, ease of use and low cost (Jindal, 2019). This makes that concrete, right behind water, is the second most used material in the world (Van Deventer et al., 2012).

In 2020 alone, about 14 billion cubic meters of concrete was used globally (Cement And Concrete Around The World - GCCS | Staging, z.d.). With this amount of concrete you can build a 6 by 6 meter tower to the moon, yearly. This comes with a great environmental impact.

Impact of concrete
Globally, the building sector contributes approximately 40% of carbon emissions (Global Alliance for Buildings and Construction et al., 2019) with cement, the binder in concrete, contributing about 8% of global carbon emissions (Andrew, 2019). The cement in the concrete alone contributes to about 90% of concrete emissions (Ove Arup & Partners Limited, 2023) due to the decarbonization process of lime (Cheng et al., 2023).

Need for improvement
To meet the Paris Agreement goals of a 55% reduction in CO2 eq emissions by 2030 and 100% by 2050 (Ministerie van Economische Zaken, Landbouw en Innovatie, 2020a), we can make huge improvements in the building sector and more specifically, the cement industry. To decarbonize (calcinate) limestone, minimal temperatures of 825 degrees Celsius need to be achieved (Kumar et al., 2007). This creates CO2 eq emissions from energy needed, when green energy sources are not used, and from CO2 release by the material.

By eliminating this step, the total emissions of concrete will lower drastically.

Improvements like this are especially called for in the current housing crisis in the Netherlands. Rijksoverheid wants to build 900,000 houses to solve this crisis, but this will only be permitted when they comply with the nitrogen laws (Ministerie van Algemene Zaken, 2023). These regulations define how much the Netherlands must reduce its nitrogen emissions, which are measured as CO_2 equivalents due to their greenhouse effects. Developing cheap and low emitting solutions to common building materials, can make building houses in this crisis possible.

Starch-based concrete
With inspiration from Kulshreshtha et al. (2017b)'s research on a corn-based binder for concrete (CoRncrete) and Roberts en Scrutton (2023)'s research on starch-based binders with materials from Mars and the moon (Starcrete), Sam de Haan did research for a similar material in his pavement application (Figure 1). This material has a bio-based binder made from potato starch that only needs low amounts of heat to bind. Together with the insight from Starcrete to press the material, Sam de Haan managed to create a material with a similar strength as common concrete (22 MPa) (SK, 2025). This lead me to believe that Sam's material could be applied in the building sector, creating a low emitting solution to concrete.

Research questions
A few challenges arise when wanting to substitute concrete with a starch-based alternative. CoRncrete has shown limitations in durability when submerged in water (Kulshreshtha et al., 2017b).

The material can deteriorate within a day, making it unsuitable for use in certain architectural applications like facades and sanitary areas. Therefore the first research question is:

1 - How can CoRncrete's water resistance be improved to meet architectural needs in wet or humid environments?

Sam de Haan's material was created for use as a pavement tile. To convert this material into an architectural material, I must consider the needs and wishes of architects to ensure feasibility and desirability. This means that application, shape, size and aesthetics will be taken into account in this material research. The next research question can be formulated as:

2 - What design characteristics make CoRncrete suitable and desirable for use as a precast architectural block?

Design goal
Since this research is done as a product design thesis, I would like to accompany research questions with a design goal. With the material being pressed, an application as a pre-cast concrete-alternative was chosen. This resulted in the following formulation of the research goal in one sentence;

"Optimizing CoRncrete into an architectural pre-cast concrete alternative by improving moisture resistance and aesthetics, while maintaining its sustainable advantage"



Figure 1 - Sam de Haan's CoRncrete samples (SK, 2025).

Introduction
Method

This graduation project aims to optimize CorNcrete into a viable architectural pre-cast concrete-alternative block, improving moisture resistance and visual qualities, without compromising on environmental performance. To do so, a method was created, roughly following the principles of the Material Driven Design (MDD) method by Karana et al. (2015) at the TU Delft. This method was chosen due to familiarity and creative freedom.

This method consists of a tinkering step, followed by a technical and experiential characterization step. In addition, context and material research are included. These two will take place simultaneously with the tinkering step, forming the second phase of the research, following phase one: the introduction. The technical and experiential characterization make up the third phase. Finally, the results from all previous phases will be combined to construct the final application, forming the fourth and last phase. (Figure 2)

Context research
To design a desirable product, research to context must be done. Researching context will be done by doing interviews with stakeholders, speaking to professionals and bench marking products in the same sector.

Material research
To substantiate the tinkering process and to create feasible solutions, material research is done. This can be in the form of desk research, speaking to professionals and learning from other concrete solutions.

Tinkering
The tinkering process will give the designer familiarity with the material by material engagement. It works via learning by doing and encourages the designer the explore as many facets of the material as possible . Designers develop a deeper understanding of the material by tinkering (Karana et al., 2015).

The outcomes of the tinkering phase will be determined with preliminary testing, using water submersion, and used to formulate research directions for in the technical characterization phase.

Technical characterization
After tinkering, material research and context research, most promising directions are identified to be taken to the technical characterization phase. In this phase, structured tests are conducted to create measurable results. These results will guide the decision making for the final design.

Tests like compression tests and water submersion will be conducted, followed by an statistical analysis of the results.

Experiential characterization
Alongside technical characterization, tests are conducted to determine the experiential characterization. These tests determine how the material is perceived by the stakeholder (Karana et al., 2015). Understanding the perception of stakeholders on your material, creates opportunities to make the material desirable and fit for the market.

Application
With the results from previous phases in mind, an application is explained. It will consider the results of technical and experiential characterization, fit in the context of the product and will proof to be the preferred sustainable choice compared to concrete.

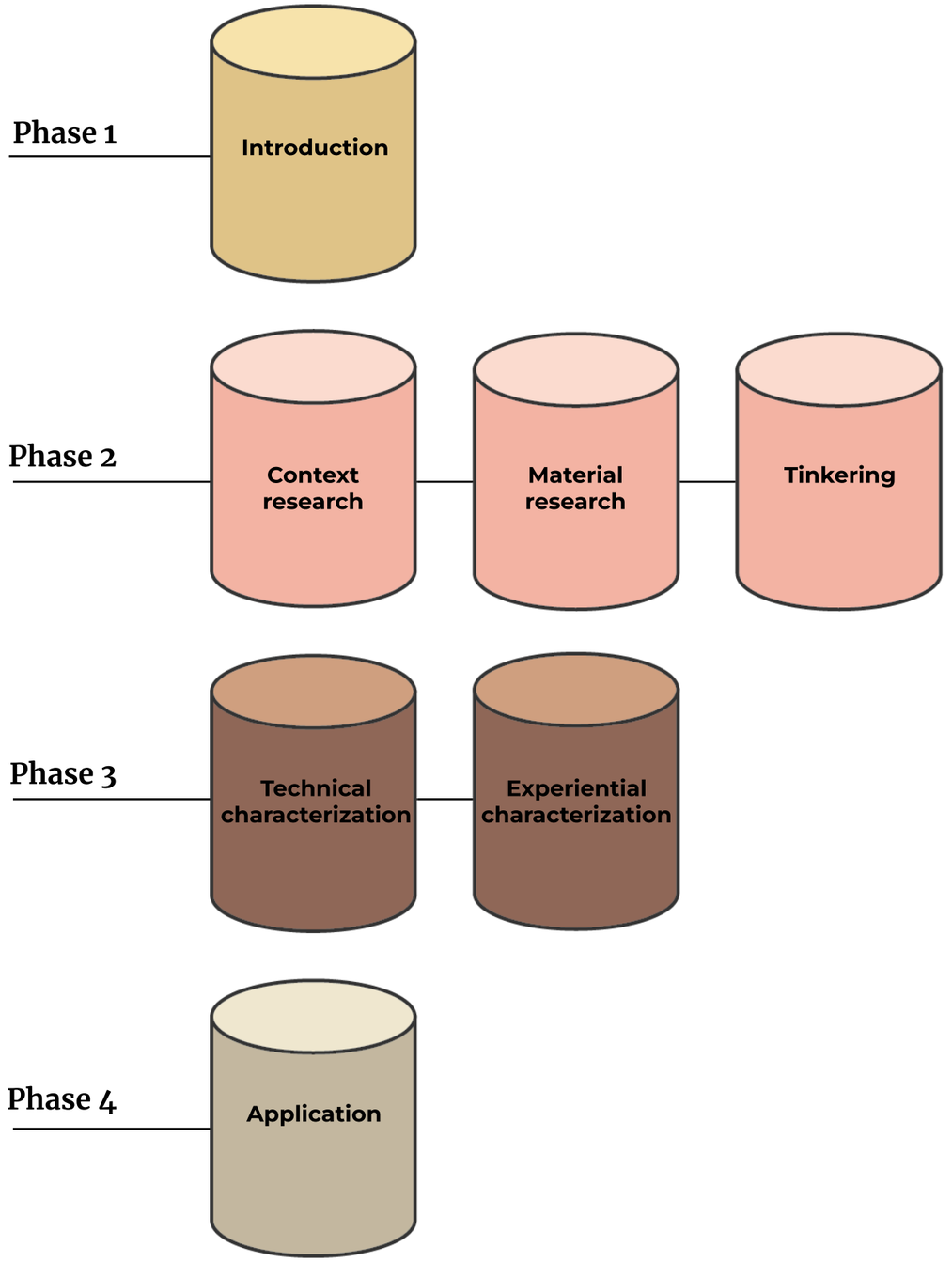


Figure 2 - Research method overview.

Introduction
Recipe 0

To evaluate the performance of any material modifications, a clear baseline is essential. Recipe 0 serves as the reference recipe in this research. It serves a consistent comparison between different formulations and treatments. A recipe consists of two key components: ingredients (the material composition) and the manufacturing method (how the material is prepared and processed).

Ingredients

Recipe 0 is based on the final formulation developed by Sam de Haan. It replaces the original corn starch with potato starch (sourced from vanbeekumspecerijen.nl), combined with sand (0.250–0.500 mm grain size, obtained from the Civil Engineering faculty), and demineralized water (demiwater) from the lab.

The ingredient proportions based on weight are as follows (Figure 3):

- Sand: 67.38%
- Potato starch: 13.37%
- Demiwater: 19.25% (including 5% rehydration water)

Manufacturing Process

The following steps outline the manufacturing process used to create samples for Recipe 0. Consistency in preparation was maintained throughout all tests to ensure reliable comparisons. (Figure 4)

1 - Mixing:
The sand and potato starch are mixed thoroughly using a whisk.

2 - Hydration:
Water is added to the dry mix and stirred again to ensure even distribution.

3 - Casting and Baking:
The wet mixture is poured into a silicone mold, covered with aluminum foil, and baked in a conventional lab oven at 120°C with 50% airflow and fan for 2 hours.

4 - Drying:
After baking, the solidified sample is broken into smaller pieces to increase surface area and speed up drying. These fragments are returned to the oven and dried at 90°C with 100% airflow and fan for 1 to 1.5 hours, depending on batch size.

5 - Granulation and Pressing:
Once dry, the material is crushed into granules using a hammer and a sieve available in the lab. These granules are rehydrated using 5% water, then pressed at 4 tonnes in a cylindric mold. Although the initial pressing was accidentally done at 4 tonnes instead of the intended 2.83 tonnes, this was maintained throughout the research for consistency.

The mold is accompanied by to pistons, a shorter and longer one. The longer one is used for initial pressing and to get the sample out of the mold after pressing. The shorter one is used for final pressing as the cavity in the mold will have the perfect 40 mm when it is inserted fully. This however, is hard to reach perfectly, which is why the samples usually tend to have a slightly bigger height.

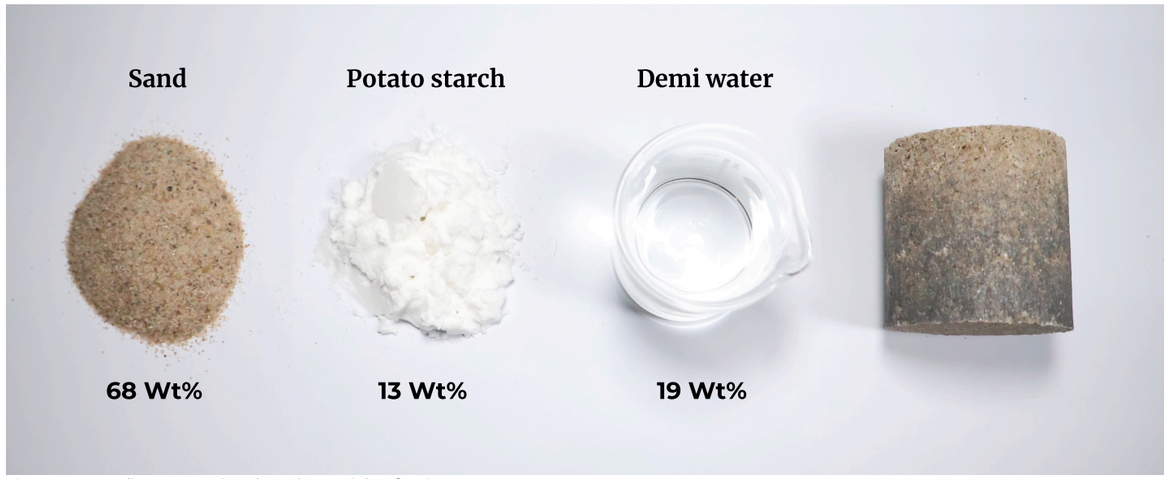


Figure 3 - Ingredient proportions based on weight of recipe 0.

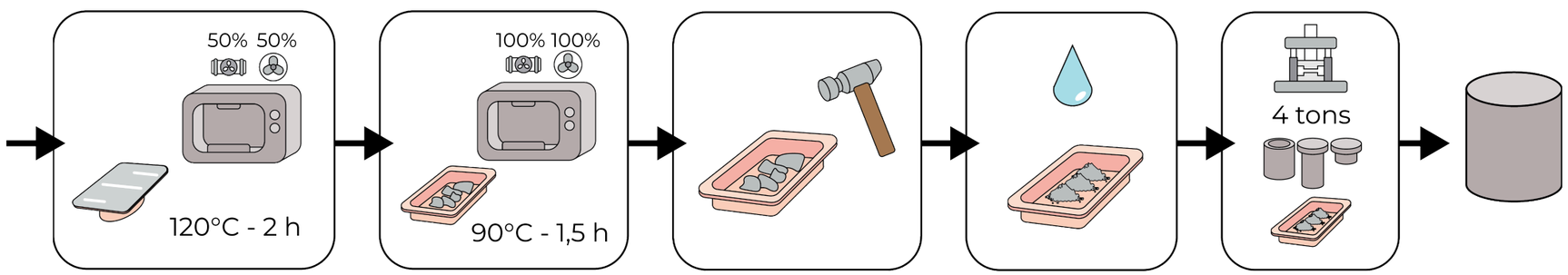


Figure 4 - Manufacturing process of recipe 0.



Context

2

Context
Bench marking

To position the material developed in this research within the current market of architectural building materials, a benchmarking study was conducted. This chapter explores a selection of comparable products that, like the proposed material, aim to serve as a sustainable alternative or solutions to conventional concrete or masonry units. The goal is to identify gaps and opportunities in the current market and to understand the minimum requirements set by the industry.

Hempcrete

Hempcrete is a sustainable building material existing of hemp hurds (the core of the hemp plant), a lime-based binder, and water. compared to traditional concrete, hempcrete is not a load-bearing material. Instead, it is used as an insulating and moisture-regulating filler within a structural framework, often made of timber. An example of Hempcrete is shown in Figure 5.

The material is usually cast on-site (in situ) into a framework to build walls, but it is also available as prefabricated panels or blocks. Hempcrete is also an excellent thermal insulation.

Another advantage is its ability to regulate indoor humidity. Hempcrete is a breathable material, meaning it absorbs and releases moisture from the air without leading to mould or condensation. This makes the material well-suited for creating healthy, comfortable living environments. Additionally, it is fire-resistant and lightweight.

Hempcrete differentiates itself as a sustainable material due to its negative carbon footprint. Hemp plants absorb more CO_2 during their growth than is emitted during the production and processing of the material. This makes hempcrete a low-impact solution for sustainable buildings projects.

However, there are limitations to consider. Since it is not structurally load-bearing, hempcrete must always be used in combination with a supportive frame. Its drying time is also relatively long, which can slow down the building process (The Effectiveness Of Hempcrete in The Reduction Of The Environmental And Financial Costs Of Residences | TU Delft Repository, z.d.) and costs money.

Overall, hempcrete is an environmentally friendly material, well-suited for energy-efficient housing, renovation projects, and biobased construction that prioritizes comfort, sustainability, and indoor health.



Figure 5 - Hempcrete example (Installatie van Hennepbetonblokken Benadrukt het Potentieel van Biogebaseerde Materialen in de Bouw | Archello, z.d.).

Rammed Earth

Rammed earth is an ancient construction technique in which layers of damp earth, often mixed with sand, gravel, and sometimes a stabiliser such as lime or cement, are compacted into a mold or framework to create solid, durable walls. This method has been re-introduced in modern architecture due to its sustainable advantages, unique aesthetic, and environmentally friendly characteristics. (Ávila et al., 2020)

The technique is usually used in warm climates (Ávila et al., 2020). Notable properties of rammed earth include its excellent thermal performance, long-term durability, and low environmental impact. The material is non-toxic, reusable, and has

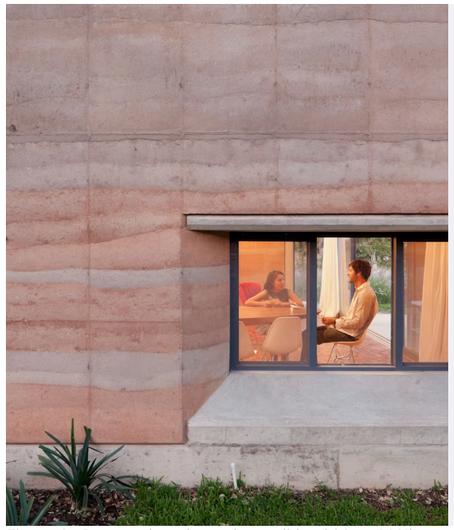


Figure 6 - Rammed earth used as wall (Architizer, 2021).



Figure 7 - Rammed earth concept sculptures showing the multiple “rammed” layers (Marshall, 2023).

a natural appearance that fits well in both rural and urban architectural settings (Bio-based Binders For Rammed Earth Construction | TU Delft Repository, z.d.).

Rammed earth can be used for both load-bearing and is comparable in characteristcs with masonry like bricks (Gomaa et al., 2023).

However, there are limitations. The material is sensitive to prolonged exposure to moisture, making careful detailing essential to prevent water infiltration (Bio-based Binders For Rammed Earth Construction | TU Delft Repository, z.d.). Additionally, construction with rammed earth can be time-consuming, because skilled labor is usually required to ensure quality. Where labor is expensive, using rammed earth will be expensive (Gomaa et al., 2023). An applications of rammed earth is shown in Figure 6 and the layers of rammed earth are shown in Figure 7.

Geopolymers

Geopolymers are inorganic polymers formed by activating aluminosilicate-rich materials, such as fly ash (Parathi et al., 2021), using alkaline solutions (Almutairi et al., 2021). Fly ash is a by product in the incineration of solid fuels and consists of non-burnt carbon, metal oxides and other inorganic components (Alterary & Marei, 2021). They offer a sustainable alternative to traditional Portland cement, by using waste stream material sources and lower emitting manufacturing processes.

The main properties of geopolymers include high compressive strength, rapid curing, chemical resistance, and lower CO_2 emissions compared to regular cement. They can achieve compressive strengths of up to 70 MPa, making them an strong and sustainable solution to regular concrete. (Almutairi et al., 2021)

Despite their benefits, geopolymers also create some challenges. With the use of fly ash, geopolymer concrete uses a by product of a heavy industry, creating an indirect need of that industry. It is however possible to make a geopolymer with many different ingredients, like glass waste (Almutairi et al., 2021), creating the opportunity for more durable solutions.



Figure 8 - Geopolymer concrete blocks (Meharchandani, 2023).

Context
Bench marking

Aluminosilicate-rich materials can be expensive hazardous, but the scaling opportunities for geopolymers are high and the performance is good, making it a somewhat financial feasible option. An example of Geopolymer concrete can be seen in Figure 8.

Bio-Cement

Bio-cement, also known as bio-concrete, is an innovative construction material in which microorganisms are used to activate calcium carbonate, which binds aggregate materials without the use of traditional cement. This process is known as Microbially Induced Calcium Carbonate Precipitation (MICP) (Liu et al., 2022).

The primary appeal of bio-cement lies in its self-healing properties, making it particularly valuable for applications in hard-to-reach or critical structural elements and maintenance applications (Nodehi et al., 2022). Notable properties of bio-cement include its low emitting manufacturing process, due to the absence of portlandcement, and its potential to capture and store CO_2 (Biomason: Revolutionizing Cement With Biotechnology, 2024).

However, bio-cement does come with challenges. The production process is complex and requires careful control of microbial activity to ensure effectiveness.Costs remain higher than traditional concrete, and with different processes, like the production of urea, new CO2 eq emissions and other environmental issues arrise (Nodehi et al., 2022). In Figure 9, you can see bio-cement strips, showing the appearance of bio-cement.



Figure 9 - Bio-cement, Biomason (FRONT® Materials (formerly StoneCycling), 2025b).

Conclusion

CoRncrete has the potential to fill a gap in the market by offering a partially bio-based material that is load-bearing, simple to produce and water-resistant with a positive cost efficiency. By meeting these criteria, CoRncrete can distinguish itself from existing materials and become a desirable option within the construction industry. Figure 10 shows the strong suits of the different bench-marked materials, showing the gaps in the market.

Requirements

The cost per unit (brick/block) should be competitive with other sustainable concrete alternatives (e.g., hempcrete blocks, geopolymer blocks), ideally not exceeding their average market price.

The production process should require fewer steps or less specialized labour than rammed earth or bio-cement production.

Whishes

Develop a fully circular product with the the use of biobased or waste stream materials.

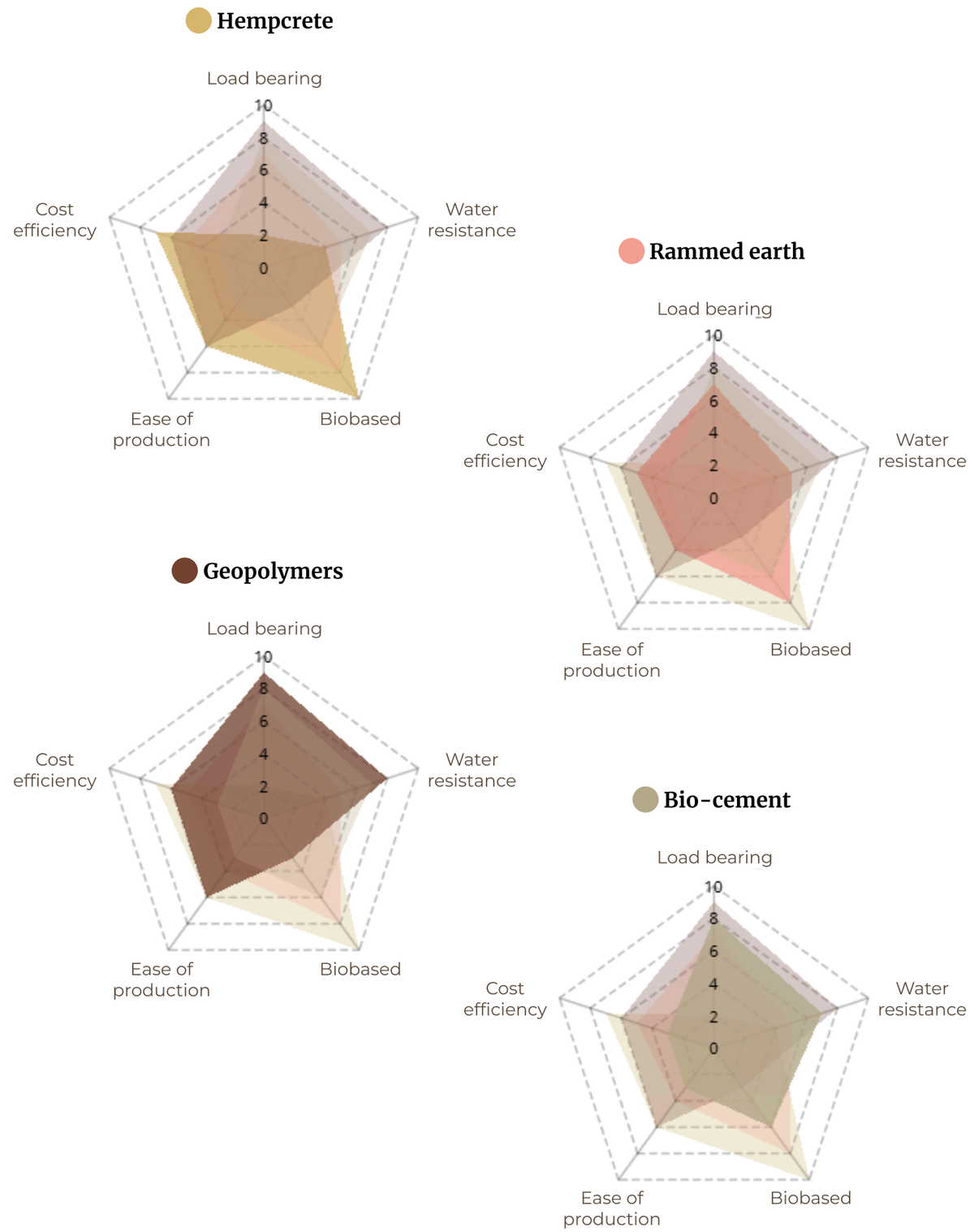


Figure 10 - Benchmarking radar-diagrams showing the strong suits of the different benchmarked materials.

Context
Interviews

For this project, I chose to focus primarily on one key stakeholder group: architects. They form an important source of information, not only because of their understanding of technical requirements but also for their knowledge of aesthetics, market developments, and common challenges in the field. To gather insights, I conducted two open conversations with architects with different backgrounds and levels of experience: one with eight years of professional experience in architectural practice with a strong involvement in biobased building innovations, and another with over twenty years of combined experience in both practice and academia, with a focus on circular building practices. Their combined expertise provided a nuanced view of the potential applications and positioning of CoRncrete within the architectural domain.

The interviews were deliberately kept open to allow for a natural exchange, with two main goals: identifying which applications of CoRncrete are most relevant for the field of architecture and gaining insight into how architects perceive the aesthetic value of a new building material.

Both interviews took place at the interviewees' workplaces. They were recorded using an app on my phone, transcribed with the help of Turboscribe (https://turboscribe.ai/), and the transcript was summarised using ChatGPT (https://chatgpt.com/). Consent for both recording and using the audio, as well as for the interview itself, can be found in Appendix A.

Relevant Applications for CoRncrete

A key theme in both conversations was the application of CoRncrete in relation to existing building practices. In the Netherlands, precast concrete is primarily used for walls, floors, and, to a lesser extent, columns.

Architects often prefer precast elements for their modularity and the efficiency they bring to construction. Without these advantages, there is little incentive to use precast over in-situ concrete.

However, it was noted that keeping CoRncrete's production process simple could limit the size of the elements that can be manufactured. This might make large-scale wall or floor panels, typical in precast concrete, more difficult to achieve. In that case, a block-based approach, similar to concrete or hempcrete blocks, could be a more viable solution. With such systems, questions arise regarding stacking methods, such as whether a dry-stack system is feasible or if mortar would be required. Besides slabs, large concrete blocks also exist, but they are not commonly used in the Netherlands.

Columns were identified as an area with interesting aesthetic potential, though their use in Dutch residential construction is relatively limited, reducing immediate market opportunities.

For wall applications, the interviewees highlighted that the standard outer wall thickness in the Netherlands is typically no more than 40 cm. Within this constraint, walls must integrate structural strength, insulation, and water/fire protection. A material that could combine load-bearing capacity with strong insulating properties would therefore offer a clear advantage. Hempcrete was discussed as an example of a material that performs exceptionally well in insulation, reducing the need for multiple layers within a wall system. However, as discussed in the previous Chapter, its lack of structural strength creates limitations. This is an area where CoRncrete could potentially provide a stronger alternative.

Aesthetic Values and Preferences

Another central theme was the aesthetic qualities of building materials. The interviewees noted that architects tend to favor materials with an "honest" or natural character. They prefer materials that show their origin through subtle irregularities, textures, or traces of the production process.

They also stressed the importance of offering a variety in color and texture, as this offers architects the option to adapt materials to their specific design vision. When I presented my current material samples, the marbled sample was particularly well-received, as it showed an more interesting visual possibility.

Both interviewees mentioned that aesthetics in architecture are mostly subjective, meaning that preferences differing widely between architects. They tried to share their opinion together with their idea of a broader accepted opinion.

Other insights

Both interviewees drew comparisons between CoRncrete and existing alternatives such as rammed earth and hempcrete. Rammed earth, for instance, was identified as one of CoRncrete's biggest competitors. it offers a sustainable, structural solution with a natural aesthetic appeal. However, its production is very labor-intensive and expensive. CoRncrete could potentially use this fap to compete with rammed earth it proves to be simpler and more scalable to produce.

Both interviewees emphasized the importance of approaching product development holistically. Materials, design, manufacturing methods, and business models should be considered as interconnected elements, together determining a product's viability and desirability.

One of the interviewees suggested "listening to the material", working with its inherent properties rather than forcing it into a prefered functional or aesthetic role. This mindset encourages developing CoRncrete in alignment with its natural behavior and production potential.

Conclusion

The conversations revealed that CoRncrete's biggest potential lies in being a modular material that could combine structural and possibly insulating properties, but only if the production process remains scalable and straightforward. Aesthetically, the material can be made attractive by focussing on its natural character and offering variation in texture and color.

By evaluating the product as a whole, including material properties, design applications, production methods, and business models, CoRncrete can be positioned as a desirable alternative within the architectural field.

Requirements

The product must be designed to allow for easy disassembly and reuse of components.

The material must function within a total wall thickness of max. 40 cm.

The complete wall assembly, including the material, must achieve an R-value of at least 4.7 m^2K/W (Isodirect B.V., 2023).

Whishes

The product should offer a line extension with multiple aesthetic options (e.g., variations in colour or texture).

The complete wall assembly could aim for an R-value of 6.7 m^2K/W, suitable for passive houses (Passive House Institute Dr. Wolfgang Feist, n.d.-b).

Context
Summary

This chapter examined how CoRncrete fits within today's market for sustainable building materials and explored its potential uses through conversations with architects.

Benchmarking
By reviewing hempcrete, rammed earth, geopolymers, and bio-cement, the study compared their environmental performance, structural behaviour, and practical constraints. With these references, a market gap was found in a bio-based product that is load-bearing, water resistant and cost-effective.

Interviews
Discussions with two architects offered further insight into how CoRncrete could be integrated into current practice. They noted that CoRncrete may work best in modular formats, blocks or smaller units, rather than large precast panels, due to its manufacture limitations using a press. They also saw room for a material that combines strength with some insulating capacity, which would respond to shortcomings in products like hempcrete, which only serves the latter. On appearance, both experts appreciated surfaces that reveal a material's origin, along with options for colour and natural texture, suggesting that CoRncrete's character could support its appeal in architectural design.

Preliminary requirements & wishes
Taken together, the findings indicate that CoRncrete could become a credible alternative to conventional concrete if its technical qualities, manufacturing approach, and market positioning are developed as one coherent strategy.

The following requirements & wishes were formulated in this chapter to structure these findings in design requirements:

Requirements
The product must be designed to allow for easy disassembly and reuse of components.

The material must function within a total wall thickness of max. 40 cm.

The complete wall assembly, including the material, must achieve an R-value of at least 4.7 m^2K/W (Isodirect B.V., 2023).

The cost per unit (brick/block) should be competitive with other sustainable concrete alternatives (e.g., hempcrete blocks, geopolymer blocks), ideally not exceeding their average market price.

The production process should require fewer steps or less specialized labour than rammed earth or bio-cement production.

Wishes
Develop a fully circular product with the use of biobased or waste stream materials.

The product should offer a line extension with multiple aesthetic options (e.g., variations in colour or texture).

The complete wall assembly, including the material, must achieve an R-value of 6.7 m^2K/W, suitable for passive houses (Passive House Institute Dr. Wolfgang Feist, n.d.-b).

Material

Material
Sealers

Following the previous chapter, which focused on adjusting CoRncrete's recipe to improve its inherent water resistance, this chapter explores an alternative approach: the use of external sealers. In collaboration with Joost van Dijk from the company Puroc and through independent research, a wide range of coatings and impregnation methods were examined. These options, varying in bio-based or waste-derived content, balance durability, sustainability, and compatibility with (partly) CoRncrete's biobased nature.

Sealers can usually be categorized into two types: surface coatings and penetrating sealers. In this report surface coatings will be called sealers. These sealers create a film over the material, creating a protective layer (Murariu et al., 2021). penetrating sealers are sealers that sink into the pores and chemically bond with the material to create a protective layer (Technology, 2023).

The choice between sealers and impregnating sealers depends on the specific requirements of the project, including solvability, waste or bio content, curing time to chemical resistance and cost.

Puroc
In collaboration with Joost van Dijk, we explored a wide range of sealers and impregnating sealers, with varying degrees of biobased or waste-based content. Some of these were developed by Puroc, while others originated from third parties. an overview of these sealers can be in Figure 11, with given information on their sealing nature, if they are water solvent, their bio content, curing time till full chemical resistance and cost catagory.

Puroc specializes in rapid-curing, chemical-resistant coatings for concrete surfaces. Their product line includes materials designed for various applications, such as warehouses and parking garages (Home - PUROC, 2019).

Acrylic impregnation
Acrylic impregnation based on a single-component acrylic polymer is a water-based treatment designed to penetrate porous materials, making it a penetrating sealer. This type of treatment is low-cost and suitable for projects where ease of application are priorities. The sealer hardens within a day. Besides water resistance, acrylic coatings can also increase a materials thermal, chemical and photochemical resistance (Chiantore et al., 1999). Water based sealers, or water soluble sealers, might have lower durability when exposed to water and might form environmental issues when solvents solve into soil water.

Impershield Euroflex
A more sustainable option is a wood-based resin known as Impershield Euroflex. It is also a water-based impregnation sealer, but stands out due to its 100% bio or waste-derived composition. Despite being eco-friendly, it still offers chemical resistance within a day, making it a balanced choice between sustainability and performance at a medium cost. Euroflex is Impershields least refined product, showing slight thermoplastic properties together with form memory. This means that the material can deform in heat, but will restore to its original form after heating (Industrial Euroflex – Impershield, z.d.).

Impershield Stone Seal
Another wood-based resin product is Impershield Stone Seal. This impregnation sealer also contains 100% bio-based material and uses water as its solvent. It is similarly effective in reaching full chemical resistance within one day and is also priced in the medium range. Compared to the other wood-based resin. This one is typically used for more porous materials like stone. The stone seal line shows different coatings that are all vapor-permeable, creating breathing materials (StoneSeal Pristone – Impershield, z.d.).

Puroc QF PUR
Puroc QF PUR is a two-component polyurethane (2K PUR) sealer. It is solvent-free and It achieves full chemical resistance in just five hours. Although it contains no bio-based content, its rapid performance and durability justify its higher cost. Joost van Dijk mentioned a client using this coating for a pool, showing its unexpected high water resistance. This coating has excellent curing abilities, being able to cure at temperatures as low as -33 degrees (QF PUR, 2019).

Puroc Flex Flow
Flex Flow, commercially known as Puroc QR 109, is another 2K polyurethane sealer. Like QF PUR, it is solvent-free. It provides chemical resistance within ten hours. This product also does not include any bio-based material and is considered high-cost, valued for its robustness and reliability.

Puroc Bio Pox
Puroc Bio Epoxy Rolcoating, or Bio Pox, is a two-component epoxy sealer with a strong sustainability profile. It contains 60% bio or waste-derived content and is solvent-free. While it requires seven days to achieve full chemical resistance, it is moderately priced and offers a compelling combination of environmental benefit and technical performance. This is also the only coating in this list with a color finish.

Puroc TR Mat
Puroc TR Mat is a two-component, water-based polyurethane sealer. It takes seven days to reach full chemical resistance and is priced at a medium level. This product offers a water-compatible alternative to solvent-based polyurethane sealers with reasonable durability. This sealer has a matte finish.

Sodium Silicate
Besides sealer options provided bij Joost van Dijk, other sealing options were also explored. Sodium silicate, also known as water glass, is used in a variety of applications, including adhesives, cleaning agents, and most importantly, for waterproofing and enhancing the durability of materials (Matinfar & Nychka, 2023). In existing concrete structures, it is applied as a surface treatment, while in new concrete formulations, it is mixed directly into the recipe. This process creates water-resistant materials (Thompson et al., 1997).

Sodium silicate can react with free calcium ions to form calcium silicate hydrate (CSH) (Firdous et al., 2021), which is a type of glassy compound. In concrete applications, cured concrete samples are treated with sodium silicate to induce this reaction, resulting in waterproof concrete (Firdous et al., 2021). These coatings are commonly referred to as silicate mineral paints.

The current CoRncrete formulation does not contain calcium; however, calcium can be introduced through the addition of eggshells. To release calcium ions, calcium oxide must first be produced. This process requires significant energy input and generates CO_2 emissions (Cheng et al., 2023). Chemical decarbonization of calcium carbonate, happens with a reaction with sodium hydroxide, producing calcium oxide and sodium carbonate. This process converts calcium carbonate into calcium oxide without energy consumption and CO_2 emissions (Simoni et al., 2022).

Treating a calcium oxide-containing CoRncrete sample with sodium silicate could potentially result in the formation of a CSH layer.

Product	Technology	Product nature	Water solvent	Waste or bio content	Full chemical resistance	Cost
Acrylic impregnation	1K acrylic polymer	Impregnation	Yes	0%	1 day	Low
Euroflex	Wood-based resin	Impregnation	Yes	100%	1 day	Medium
Stone Seal	Wood-based resin	Impregnation	Yes	100%	1 day	Medium
QF PUR	2K poly urethane	Sealer	No	0%	5 hours	High
Flex Flow	2K poly urethane	Sealer	No	0%	10 hours	High
Bio Pox	2K epoxy	Sealer	No	60%	7 days	Medium
TR Mat	2K water based poly urethane	Sealer	Yes	0%	7 days	Medium

Figure 11 - Overview of sealers provided by Puroc with their characteristics.

Material
Sealers

This layer would develop within the pores of the sample where the water glass penetrates. The resulting "glassy" layer prevents water from infiltrating the material, thereby making CoRncrete water-resistant.

Linseed oil

Linseed oil is the main ingredient in linoleum. In this biobased material, linseed oil is oxidised together with tree resins, then mixed with fillers such as wood flour and chalk, and finally dried to form a rubber-like sheet. During this process, the linseed oil polymerises, creating strong molecular bonds within the material. (Marmoleum | Hoe het Wordt Gemaakt | Forbo Flooring Systems, z.d.)

The resulting linoleum, marketed under the name Marmoleum by the Dutch producer Forbo, shows a high resistance to water with or without closing the seams between sheets (Marmoleum Linoleumvloeren - Forbo Flooring, z.d.).

Hydrophobic materials naturally repel water. Using this effect to improve the water resistance of CoRncrete could be a potential solution. To replace part of the water in the recipe with oil (while still retaining some water for the starch reaction), an emulsion needs to be created. In cooking, this is often done with egg yolk. An egg yolk contains both hydrophilic and lipophilic properties, due to its high protein and phospholipid contents, which allows it to bind oil and water together (Xu et al., 2024). Besides egg yolk, containing lecithin, there are other natural emulsifiers that can be used such as pectins and gelatins (SVREditor, 2024). In the lab I worked in we had apple pectin or cellulose gum which could be used for emulsifying. An example of a Forbo marmoleum floor can be found in Figure 12.



Figure 12 - Forbo marmoleum (Linoleum, Lino, Forbo, z.d.).

Conclusion

The exploration of sealer options highlights that there is no single universal solution for improving CoRncrete's water resistance. Conventional polyurethane and epoxy-based sealers offer high durability and quick performance but are less focussed on circular and biobased goals. In contrast, wood-resin impregnations, sodium silicate treatments, and linseed oil-based solutions provide more sustainable options, although they score lower in curing time, cost, or technical performance. These options will also be tested during the tinkering step.

Material
Recipe adjustments

In this chapter, options for improving the water resistance of CoRncrete are explored. The focus lies primarily on modifying the material's composition by experimenting with alternative or supplementary ingredients or manufacture methods that can enhance its performance. This investigation combines insights from literature research and discussions with experts. This exploration is in line with the first research question.

Eggshells

During an event at the Faculty of Architecture on end-of-life strategies in the built environment, I spoke with the co-founder of Eggxpert, a company exploring circular innovations with eggshell waste.

With the increase in egg production, it is expected that the global egg industry will produce about 8 million tonns of eggshells yearly (Sathiparan, 2021). Although a part of this waste-stream is used in medical or dental therapy and/or as component in biodiesel (Faridi & Arabhosseini, 2018), most of the eggshells waste does not have a purpose (Sathiparan, 2021b). Eggxpert aims to valorize this residual stream by developing innovative applications for it, for both skincare and lime-replacement (EGGXPERT - Make Waste Wonderful, 2025).

Eggxpert expressed interest in collaborating on new applications using eggshells. With limestone ($CaCO_3$), being a common ingredient in conventional concrete mixes (Dinis-Oliveira et al., 2014), the idea occured that eggshells could potentially be incorporated into CoRncrete. Eggshells are a very pure source of CaCO3 with about 96% CaCO3 contents (Gomez-Vazquez et al., 2024).

As it turns out, I wasn't the first to consider this. Several studies have explored the effects of eggshell powder as a partial replacement for cement in concrete. These studies often reported improvements in both compressive strength and water resistance (Chong et al., 2020)(Doh et al., z.d.)(Tiong et al., 2020) when used in specific ratios. This aligns remarkably well with the goals of CoRncrete as a biobased, water-resistant and load bearing material.

Many types of cement undergo high-temperature processing that transforms calcium carbonate ($CaCO_3$), such as found in limestone or eggshells, into calcium oxide (CaO). When mixed with water, calcium oxide reacts exothermically to form calcium hydroxide ($Ca(OH)_2$). Upon exposure to CO_2, this compound carbonates back into calcium carbonate. This chemical cycle is known as the lime cycle (Dinis-Oliveira et al., 2014), and eggshells can follow this same transformation (Gomez-Vazquez et al., 2024). This cycle is shown in Figure 13.

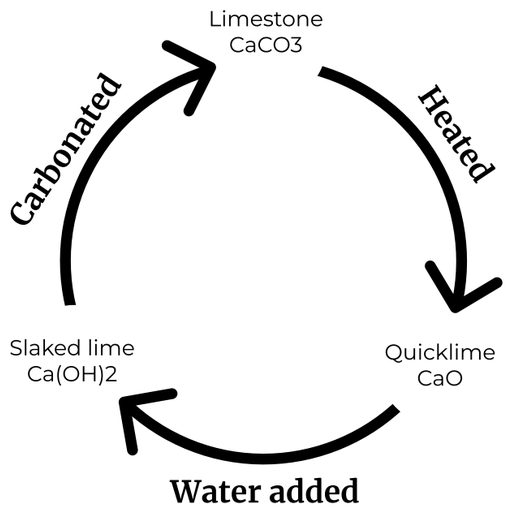


Figure 13 - Lime cycle.

Beyond acting as a reactive compound in cement replacements, calcium carbonate (in the form of ground limestone) is also used as a fine aggregate in concrete mixes without undergoing the lime cycle.

Research suggests that the addition of unheated limestone can slightly improve compressive strength and elasticity (Aquino et al., 2010). This implies that calcium carbonate, even without being calcined, could positively influence the mechanical properties of CoRncrete as well.

In terms of environmental performance, eggshell powder presents an interesting case. As a waste product, its carbon footprint is significantly lower than mined calcium carbonate.

Cow Dung

Cow dung in India has been used as a construction brick for centuries, calling it "Gobar bricks" or "Cow dung patties", because of its water resistance and pest repelance ("Development And Study Of Cow Dung Bricks", 2024). Even today, it continues to serve as an accessible and sustainable resource for natural building techniques ("Development And Study Of Cow Dung Bricks", 2024).

280 million kilograms of nitrogen is emitted yearly in the Netherlands due to animal manure (Centraal Bureau voor de Statistiek, 2024). With derogation ending, an increase of the Dutch manure sur-plus is expected, resulting in about 400.000 trucks in 2026 of manure that cannot be used in the country (Van Noort, z.d.). With coming policies involving nature development, it is expected that this sur-plus will double (Van Noort, z.d.).

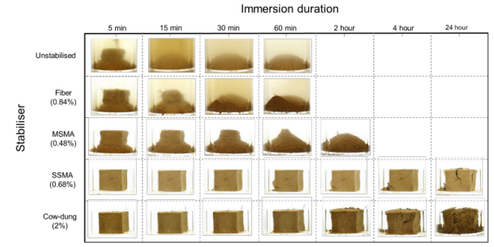


Figure 15 - Cow-dung water resistance performance in clay bricks when submerged in water (Kulshreshtha et al., 2022).

If not spread on lands, this sur-plus is either exported or incinerated (Mestafzet Buiten de Landbouw, 2000-2023, z.d.).

With manure being a waste stream and it emitting high levels of CO2 eq when incinerated, it forms an intersting material source. Research shows that materials treated with cow dung can remain structurally intact for 12–24 hours longer when submerged in water, compared to untreated counterparts (Ngowi, 1997). This suggests its potential as a natural water-resisting additive in sustainable construction materials.

Yask Kulshreshtha, one of the early inspirations for CoRncrete, conducted research on cow dung which resulted in a material concept called Moobricks (Kulshreshtha et al., 2022). His work focused on identifying the specific components in cow dung that contribute to its water-repellent properties. A collaboration between the findings of Moobricks and the CoRncrete project could potentially lead to a stronger, more durable formulation.

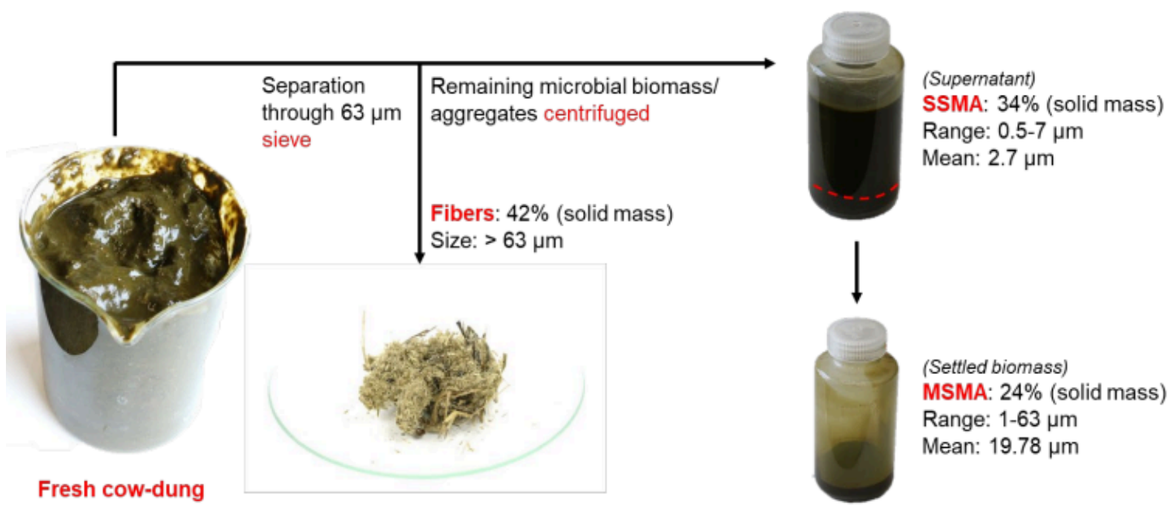


Figure 14 - Cow-dung contents and seperation explenation of the different contents (Kulshreshtha et al., 2022).

Material
Recipe adjustments

Yask Kulshreshtha found that Small-Sized Microbial Aggregates (SSMAs) in cow dung are primarily responsible for its hydrophobic. properties. Aggregates are granular materials. These microbial structures are rich in fatty acids, which naturally repel water. The SSMA fraction is extracted by first removing the fibrous content of the dung, followed by centrifugation. The liquid "decanted" phase, separated from the solids, contains the active SSMA component (Figure 14). While raw cow dung already improved water resistance in materials, the use of pure SSMA yielded the most significant results (Kulshreshtha et al., 2022) (Figure 15).

When contacted about integrating SSMA into the CoRncrete process, Yask pointed out a practical challenge: heating SSMA produces a particularly unpleasant odor. Notably, Yask's version of CoRncrete had not yet included a compression stage in the manufacturing process. This opens the possibility of adding SSMA later, as part of the final 5% water addition right before compression, avoiding the need to heat it.

In a broader circularity context, Floating Farm, an urban agricultural initiative based in Rotterdam, has also expressed interest in finding value-added uses for their cow dung. Floating Farm is a dairy farm located on water, housing 26 cows. The farm aims to develop a sustainable farming method by creating a circular system within the farm and its surrounding environment. Floating Farm receives carbohydrates and proteins from the city in the form of food waste, which is then converted into feed for the cows. The cows' manure is partly processed into water for the on-site vegetable garden. Both the vegetable garden and the milk produced by the cows provide carbohydrates and proteins for the local community. In this way, they try to create a closed-loop system as much as possible. The images on the right side of this page give show the Floating Farm.

Sam Otte, who assisted and guided me around the site, mentioned that there are significant surpluses of cow manure that cannot be locally processed and therefore are either exported or incinerated. For this reason, Floating Farm is actively collaborating with designers and researchers who transform cow manure into materials. For example, bricks and various bioplastics have already been developed from manure.

The manure is first separated into a solid and a more liquid form (liquid manure), with the latter containing a high amount of urine. The liquid fraction undergoes further treatment to remove harmful substances, and the remaining water can then be used for irrigating plants.

The liquid manure most closely resembles the SSMA (Solid State Microbial Analysis) from Yask's research. In addition to liquid manure, I also collected a bucket of regular cow manure, as several other researchers have made interesting products from it.

Sam also described an in-house project involving a plant pot made from manure and lime. This porous material is not fully waterproof but can resist water. This means it absorbs water in its pores and allows it to pass through, but the material itself does not get damaged. This property seems promising for indoor building materials that are vapor-permeabl

Silica Fume

Following a recommendation from Niki Loonen, a sustainable concrete consultant, I began exploring silica fume.

Silica fume is a by-product of silicon production (Prem et al., 2019) and consists of extremely fine particles between 0.1 and 0.3 µm (Panesar & Zhang, 2020). It is widely used in the cement industry due to its pozzolanic reaction with calcium hydroxide, resulting in strong bonds (Mitchell et al., 1998).



Material
Recipe adjustments

By combining silica fume with other granular materials such as sand and lime powder, a mix is created with particles of various sizes. These particles can potentially fill each other's pores, reducing the available space for water to penetrate through the material.

Niki Loonen recommended a formulation using sand, lime powder around 0.01 mm and 0.002 mm particle sizes, paired with silica fume. This recipe combines both phenomena by mixing different particle sizes with a pozzolanic reaction between the silica fume and the lime powder in the formulation. Niki expects that this addition could potentially double our current compressive strength.

To ensure the pozzolanic reaction takes place, calcium oxide must again be added. It may also be interesting to investigate whether silica fume can react directly with calcium carbonate. When adding water to the eggshell powder, I observed a slight exothermic reaction (heating). This could indicate that the lime powder is fine enough to engage in reactions that normally require prior oxidation.

Conclusion
The exploration of eggshells, cow dung, and silica fume reveals multiple promising pathways for improving the water resistance of CoRncrete.

Eggshells offer a highly pure source of calcium carbonate, which can strengthen the material and increase its water resistance. Cow dung, particularly its SSMA fraction, introduces natural hydrophobic properties, while silica fume, as a by-product of silicon production, refines the material's microstructure and enhances compressive strength through pozzolanic reactions. These materials will be investigated as separate options for improving CoRncrete's formulation in the tinkering step.

Summary
In this chapter, several options were explored to improve the water resistance of CoRncrete, with a focus on both recipe changes and sealers.

-Sealers
Different sealers were reviewed, from fast-curing polyurethane and epoxy sealers to bio-based wood resins, sodium silicate, and linseed oil. Each option was weighed against its water solvability, the time it needs to cure, its costs, and how high its bio-based level is. The conventional polyurethane and epoxy-based sealers proved highly effective and quick, whereas the wood-resin, silicate, and oil solutions scored better on sustainability. These, however, required longer curing or offered less durability.

-Recipe adjustments
The research also examined materials that could be mixed into CoRncrete itself. Finely ground eggshells stood out as a pure source of calcium carbonate, with prove of improving strength and water resistance in concrete. Elements in cow dung, particularly the so-called Small-Sized Microbial Aggregates, showed hydrophobic **behavior** that might be harnessed in construction. Silica fume, an industrial by-product, was identified as a way to refine the pore structure and create additional bonds, improving density and strength.

Taken together, these studies show a broad scope of options to increase the water resistance of CoRncrete. In the next chapter, these options are tested in the current CoRncrete mixture, to evaluate their behavior in this specific application.



Tinkering

4

Tinkering
Method

Building on the knowledge gained in the previous chapters, Chapter Y, which explored recipe modifications to improve CoRncrete's water resistance, and Chapter X, which examined the potential of various sealers—this chapter focuses on practical experimentation. Through tinkering, small-scale samples were created and tested to gain a first impression of how these strategies influence the material's performance.

This hands-on phase serves as an important step toward answering the first research question of this study, as it provides early insights into the material's water resistance and mechanical behavior in response to the explored interventions. Where possible, results from preliminary tests, primarily consisting of water submersion tests, are shared to inform the next stages of development.

In addition, the tinkering for aesthetics subchapter marks the beginning of an exploration related to the second research question, focusing on the material's visual and tactile qualities. At this stage of the research, these aesthetic evaluations will be assessed primarily based on my own expertise and opinion, providing an initial framework for further, more systematic investigations.

Water resistance test

All samples with potential interesting water resistance results, and one reference recipe 0 sample, were used in the water resistance test. The relevant samples and results will be found in the respective subchapters. In the second phase, the water resistance test will be in the form of a water absorbtion test using submergion following the BS 1881: Part 122 standard (British Standard, 1983). This standard was used in water resistance tests on concrete samples with eggshell filler ("Eggshell Powder: Potential Filler in Concrete", z.d.)

All samples (give range in sizes) will be weighed before the test. The samples will be submerged in water and will be monitored after 10 minutes for 4 times and after that after 30 minutes, later 1 hour and lastly steps of 2 hours. This depended on the amount of activity monitored in the mean time. Between time periods there are weighing periods that take a few minutes. If a sample seems to start dissolving, the sample will be taken out of the water in the hope that a compression test can still follow. during the night, the sample that remain will stay in the water and are checked on the next morning.

The monitoring includes weighing the samples and observing their behavior in the water. Weighing is done on a Gvolatee kitchen scale after the samples are gently dabbed dry with a cloth. After weighing, the samples are put back in the water. All samples lay in a seperate glass or ceremic bowl with white background.

A Brinno time laps camera, set on 30 seconds, is used to follow the behavior of the samples together with random foto's using my phone. The test setup can be seen on Figure 16, 17 and 18.



Figure 16 - Submerge test setup showing camera setup.



Figure 17 - Samples in water during submerge test.



Figure 18 - Submerge test setup scale for weighing samples.

Tinkering
Sealers

This subchapter documents the tinkering process with various sealer options to improve CoRncrete's water resistance, based on the knowledge gathered in the previous chapter. Several sealers with different chemical compositions, curing times, and sustainability profiles were tested. These preliminary experiments, mainly assessed through water submersion tests and my own expertise, provide initial insights into their effectiveness. In the end, conclusions are drawn on which options could be promising for further exploration in the next research phase.

Sealers brought by Puroc

In collaboration with Joost van Dijk from Puroc, we tested a wide variety of Sealers (sealers and impregnators) (Figure 19 & 20). They assisted with the application and determined the appropriate ratios based on molecular bonding. They also advised when it was especially important to handle the coatings carefully, for example to avoid skin contact. We applied an extra layer to impregnation samples because these sealers penetrate the material rather than forming a surface layer, which makes it harder to spot where parts may not be covered enough.

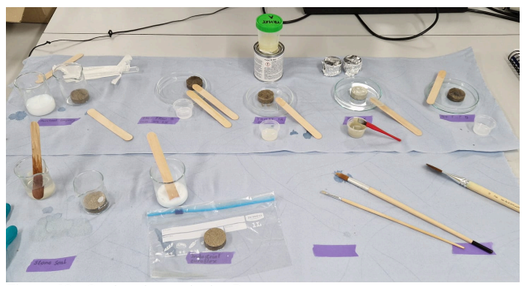


Figure 19 - Sealers brought by Puroc.



Figure 20 - Coated samples with sealers brought by Puroc (Industrial Euroflex, Bio Pox, Acrilic impregnation, Stone Seal, QF Pur, Flex Flow, TRMAT.

Since each sealer had different properties, the application methods varied. Some were coated all around immediately using a brush, while others required coating one side first and then the other side afterward. For this reason, the Bio Pox coating needed to be reapplied the next time. Although this coating has a curing time of seven days, the sample could be flipped after just one day to coat the other side.

The Impershield Stone Seal sealer was the only one to visually damage the sample, forming cracks and softning it (Figure 21).



Figure 21 - Crack in Stone Seal coating sample.

The sealers sometimes stuck to the glass of the petri dishes. In particular, the QF Pur coating hardened significantly, requiring me to carefully pry the sample loose with a knife.

Linseed Oil

I applied a layer of linseed oil with a brush to an existing sample of recipe 0 (Figure 22). The sample was left to dry in a petri dish for one day before applying a second coat with a brush. Afterward, the sample was allowed to dry further until additional tests were conducted. After the first day, the sample appeared reasonably dry, but the day after the second coat, it became very oily.



Figure 22 - Linseed oil coating on sample with oil and brush.

Sodium Silicate

Rather than decarbonizing eggshells at high temperatures, which would create emissions and was impractical at this phase, I attempted to introduce calcium oxide directly into the recipe. However, when combining calcium oxide with water and mixing it with the rest of the ingredients, the mixture became hot enough to activate the potato starch before properly mixed, causing it to clump. This made it impossible to properly prepare a smooth sample for later treatment with sodium silicate.

While this approach proved unworkable, the experiment suggests that heating a calcium carbonate-containing sample to decarbonize it before applying sodium silicate could make this method feasible in future research.

Water resistance test

The linseed oil coating lasted slightly longer than the sample with linseed oil mixed into the material itself, but after roughly 10 minutes in water, the coated sample began to break down. To preserve the sample for potential future testing, I removed it from the water at that point.

In contrast, the coatings provided by Puroc performed significantly better. They all withstood water exposure for a much longer time. When failure eventually occurred, it typically manifested as cracking or bursting (Figure 23). This suggests that water builds up inside the material, and once the internal pressure becomes too great, the coating can no longer contain it.

The failure times varied by coating:

- Industrial Euroflex and Bio Pox showed signs of failure between 100 and 130 minutes.
- QF Fur failed between 190 and 220 minutes.
- Flex Flow lasted the longest, with failure occurring between 460 and 520 minutes.
  (Times for the remaining samples will be added once testing is complete.)



Figure 23 - Sealers bursting open.

Most of the sealers retained a solid and stable feel until close to the point of failure. In some cases, they began to feel slightly soft or squishy toward the end, as far as I could observe.

The Stone Seal sample occasionally felt slightly grainy when removed from the water, as if tiny grains of sand were coming off. Still, despite a visible crack that formed during the coating process, this sample performed impressively well.

The most promising options were Acrylate Impregnate, Stone Seal, and TR MAT with 18,34%, 7,09% en 18,40% weight increase by the water in 24 hours. The Stone Seal sample showed cracks after drying, the Acrylate Impregnate sample showed little difference and the TR MAT sample seemed to have a stretched layer of coating around the sample, which created a soft look on the sample

Conclusion

Overall, the sealers performed very well in terms of water resistance. The sealers that performed a little less, are assumed to have had water build up in the sample. this could be the result of poor sealing. The linseed oil sealer did perform lowest of sealers, but might have potential with additional curing time and/or the use of catalysators.

TR MAT has a longer drying time and falls within a similar price range as Stone Seal. Acrylate Impregneer is more affordable and offers similar drying characteristics. However, for the purpose of this project and to support the narrative of using sustainable materials, Stone Seal was selected as the preferred option.

Tinkering
Recipe adjustments

This subchapter documents the tinkering process of experimenting with possible recipe modifications to improve CoRncrete's water resistance. Small-scale samples were created and tested, primarily through water submersion tests, to gain a first impression of their performance.

These preliminary results provided insights into which adjustments show the most promise. In conclusion, this chapter identifies which options could be worth exploring further in the next phase of research.

Eggshells

Using the information gathered during the material research phase, I conducted several tests involving eggshells. Research indicates that a small addition of eggshell powder can slightly improve water resistance and overall material quality. Through Eggxpert, I obtained two sizes of eggshell powder (2-3 mm and 50 µm). The larger eggshell particles were mainly for aesthetic purposes.



Figure 24 - 10% sand replacement, eggshell powder 50 µm after drying.

To start, I prepared a sample where 10% of the sand, about 7% of the ingredients, was replaced with eggshell powder, because 10% replacement showed optimal results in Chong et al. (2020)'s research. The amount of sand equivalent in their research was not comparable to the recipe in this report, but for the sake of consistency, This percentage was copied. The mixture became noticeably more paste-like than the original recipe. Right after mixing, a thin layer of moisture appeared on the surface, as if the water was separating. After drying, the material became extremely hard, making it difficult to manually crush the stones into granules (Figure 24).

I repeated the recipe, but instead of drying the baked pieces immediately in the oven, I broke them into smaller parts and placed them directly into the mold. The dough expanded out of the mold due to excess moisture (Figure 25). The paper under the mold partially stuck to the sample. I then placed the sample with the mold into the oven alongside other samples to continue drying and left it overnight in the mold for further drying. When I made the recipe a third time, no moisture layer appeared, and the stones were slightly less hard, possibly due to errors in the first or second attempt.



Figure 25 - 10% sand replacement, eggshell powder 200 µm wet mixture in mold.

In addition to this, I conducted two other tests with eggshell powder: one replacing 100% of the sand (10% fine ground, 90% coarse ground), and another replacing 5% of the sand (fine ground). The 100% sand replacement was purely for aesthetic purposes. These stones were very crumbly, and the final cylindrical sample did not seem very strong (Figure 26). More details on this sample are provided in the next chapter.



Figure 26 - 100% sand replacement, eggshells powder 2-3 mm and 50 µm after drying.

The 5% sand replacement seemed to behave as an intermediate between the original recipe and the 10% sand replacement during manufacturing. All samples with the 100% sand replacement in it, started to mold after a week or two.

Interesting to notice is that, when water is added to a 10% eggshell replacement mix, you can see the water rolling of the rest of the ingredients. In recipe 0 it sinks into the mix immediately. This might already show the eggshells water resisting properties

Cow-dung

Two types of samples were made using cow dung. One was created with liquid cow manure, which should most closely resemble the SSMA component described in Kulshreshtha et al. (2022)'s research. The other type was made with fresh, unprocessed cow dung. The containers holding the material, especially early on, had to be vented regularly due to gas buildup. This meant leaving the lids off at times (Figure 27).

For the SSMA-like samples, I used a dosage of approximately 0.68% based on a simplified assumption of 100% water content in the liquid manure. This translated to replacing about 2.5 grams of water in the CoRncrete recipe with the cow manure. For the fresh cow dung variant, I replaced part of the CoRncrete aggregate with raw dung. The composition was approximately 5% demi-water, 85% CoRncrete aggregate, and 10% fresh cow dung. Because the mixture quickly became too wet, I ended up lowering the water content by 2.5 grams. Even with the adjustment, the mix remained quite liquid and overflowed from the mold during pressing (Figure 28). The final sample feels less solid and emits a fairly strong odor.

The resulting samples looked similar to Sample 0, but had a noticeable cow manure odor.



Figure 27 - 2 types of cow-dung, fresh unprocessed and liquid, venting.



Figure 28 - Cow-dung slightly overflowing mold.

Silica fume

Due to health related risks with this material, I was unable to perform tests due to my lack of experience in a lab. Further research my still be relevant.

Tinkering
Recipe adjustments

Linseed oil
Two types of tests were performed with linseed oil. One as an additive to the recipe and the other as a coating. In this chapter, I will discuss the first.

I replaced the added water with a water/ linseed oil emulsion. To create the emulsion, I used a cellulose gum emulsifier to bind the water and oil (Figure 29).

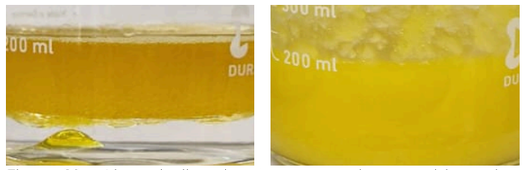


Figure 29 - Linseed oil and water seperated vs. emulsion using cellulose gum.

A larger volume of emulsion was required compared to the amount of water normally added, as the mixture was not dough-like enough. After baking, the samples were oily and brittle. They remained this way even after drying. During pressing, oil leaked out from all sides of the mold. The sample is relatively solid but oily and feels somewhat unstable and fragile.

New manufacture method
During the tinkering with eggshells, a new manufacture method was developed where the mixture is not dried after the baking time, but immediately pressed in the mold. The drying time happens when the sample is already in its intended shape. This method was also applied on recipe 0. With this sample, it can be determined if the new manufacture method has effects on the water resistance of the sample.

Water resistance test
The sample that contained linseed oil in the mix disintegrated immediately upon submersion, turning into a pudding-like consistency (Figure 30). Similarly, the sample with 10% eggshell content also broke apart right away (Figure 31), although in this case, the edges dissolved gradually rather than


Figure 30 - Linseed oil in mix and recipe 0 submerged.


Figure 31 - 10% sand replacement submerged

all at once. Recipe 0, the SSMA sample, and the 5% eggshell sample all showed slight surface dissolution from the start. However, the breakdown was not severe enough to stop the test immediately. These samples were removed after 10 minutes, at which point they were weighed. Recipe 0 and the SSMA sample completely crumbled with just slight pressure from a fingertip—this was not the case for the 5% eggshell sample, which remained relatively more stable.

The cow dung sample held up surprisingly well and never dissolved. After approximately 100 minutes, a visible crack started to form in the center. When dried, the sample left brown stains on the cloth, indicating some material bleeding.

The 10% eggshell and recipe 0 sample that dried after pressing in the mold, performed best of all the recipe modifications. They even outperformed several of the coated samples in water resistance. During 24 hours, the samples increased in 12% and 11.55% weight respectively, due to the water. When dried for a day after the water resistance test, the eggshell sample formed a few cracks. The recipe 0 with new manufacture method lost some weight due to the dissolving of the outer layer of the sample, But stayed sturdy underneath that. The eggshell sample became spongy feeling after laying in the water for a longer period of time. Additionally, the recipe 0 sample with new manufacture method felt somewhat slimy when taken out of the water.

Conclusion
The 10% eggshell and recipe 0 sample, dried in the mold, showed excellent performance and deserves further Exploration. It is assumed that the long water resistance originates in the new manufacturing method used. Using eggshells in addition to the new method showed pros and cons. It seemed that the use of eggshells in combination with the new manufacture method, made the sample more spongy than recipe 0 with the same method, but did prevent the sample from partly dissolving (outer layer). Therefore, an exploration with different levels of eggshell additions might be worth exploring.

Tinkering
Aesthetics

This chapter focuses on the second research question, exploring the aesthetic potential of CoRncrete. Just as the other tinkering chapters, the process is aimed at experimenting, now with different shapes, textures, and colors to gain an initial understanding of the material's visual and tactile possibilities. With these insights, the basis for the end design is determined.

Pigments

I used lacquer red from the paint mill "De Kat." It produced a beautiful color when adding 10 grams on top of recipe 0 (Figure 32). The sample seemed slightly softer (somewhat tender), but this was not officially tested. Using slightly less pigment might be a better idea. This pigment was also combined with pieces of non-pigmented mix, resulting in marbled samples.



Figure 32 - Verfmolen De Kat Lacquer red pigment in recipe 0 mixture.

Replacing the water in the recipe with vegetable pigment water was not very successful (Figure 33). With cooking water from coffee grounds, beetroots, red cabbage and



Figure 33 - Color result of vegetable pigment (beetroot) in recipe 0.



Figure 34 - Ingredients for vegetable pigments (coffee grounds, beetroot, red cabbage and spinach.

spinach (Figure 34), the colors were very faint. Either the pigment concentration in the water needs to be stronger, or I should focus on using powdered pigments.

Textures

Using wooden sticks, I created ridges which add some visual interest. This could be incorporated as a large-scale mold texture. The texture was applied using leftover grains (both hydrated and non-hydrated), resulting in a rough surface. However, this texture option is not feasible when pressing is involved. (Figure 35)



Figure 35 - Texture and colour experiments using wooden sticks, and leftover CoRncrete grains.

I also applied surface texture with some house hold ingredients like piment, juniper berries, eggshells and corn grains (Figure 36). This diplayed the visueal qualities of a terrazzo look.



Figure 36 - House hold ingredients surface texture (piment&juniper berries, eggshells and corn grains.

Different additives also produce different textures. Samples with 100% eggshell look completely different from recipe 0. Even a 10% eggshell addition already gives a softer appearance. Mixing these two options with some pigment grains creates a kind of speckled or terrazzo vibe. (Figure 37)



Figure 37 - Eggshell aesthetics from different eggshell additives.

The coatings also affect the appearance of the samples. Some look quite similar, perhaps a bit more "hydrated", while others are very glossy. One sample even has pigment incorporated into the coating.

Oxides

For a previous sample, I used pigments from Verfmolen De Kat , a traditional Dutch windmill where paint is still ground in an artisanal way (Figure 39). That sample used a synthetic pigment, but for this research I visited the mill and, together with the miller, searched for a more sustainable option. Paint ground by a mill is already relatively sustainable in itself, as the grinding process is powered by wind.

We decided to work with oxides. Oxides are colors that come from the earth. They are minerals or metals that get their color through a reaction with oxygen. They are ground into a fine pigment powder and provide strong, natural coloring.

Five options were chosen from the mill (Figure 38):
-Burnt umber
-Spanish red
-Roof tile red (Ground traditional Dutch roof tiles. not an oxide, but a circular pigment).
-Ochre yellow
-Green Bohemian earth

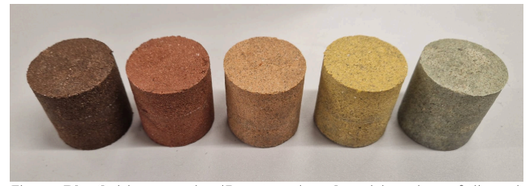


Figure 38 - Oxides samples (Burnt umber, Spanish red , roof tile red, ochre yellow, green bohemian earth).

As seen in the photo, the colors generally adhered very well, except for the Bohemian green, which showed significantly weaker pigmentation.

Conclusion

Due to the use of heat in the manufacturing process, it seems like using a DIY vegetable pigment is not feasible with the current approach. Using powdered pigment seems more promising and can be further explored. Clean and sharp shapes can be achieved after baking. If this is also possible in a press is to be determent. For this, a new mold should be created. Adding different materials to the surface for a texture could be interesting, but should be explored further for practicality.

Oxides prove to be the best option for coloring, thanks to their natural origin, strong pigmentation, and the sustainable production method at the windmill. The pigment made from ground roof tiles seems less viable as a long-term solution, due to its limited availability. In addition, one of the oxides is a calcined (fired) pigment, which involves CO_2 emissions, and the Bohemian green is not pigmented enough to be a strong candidate. Nevertheless, I will keep all of these pigments in consideration for the final design phase.





Figure 39 - In-house pigments & windmill De Kat.

Tinkering
Summary

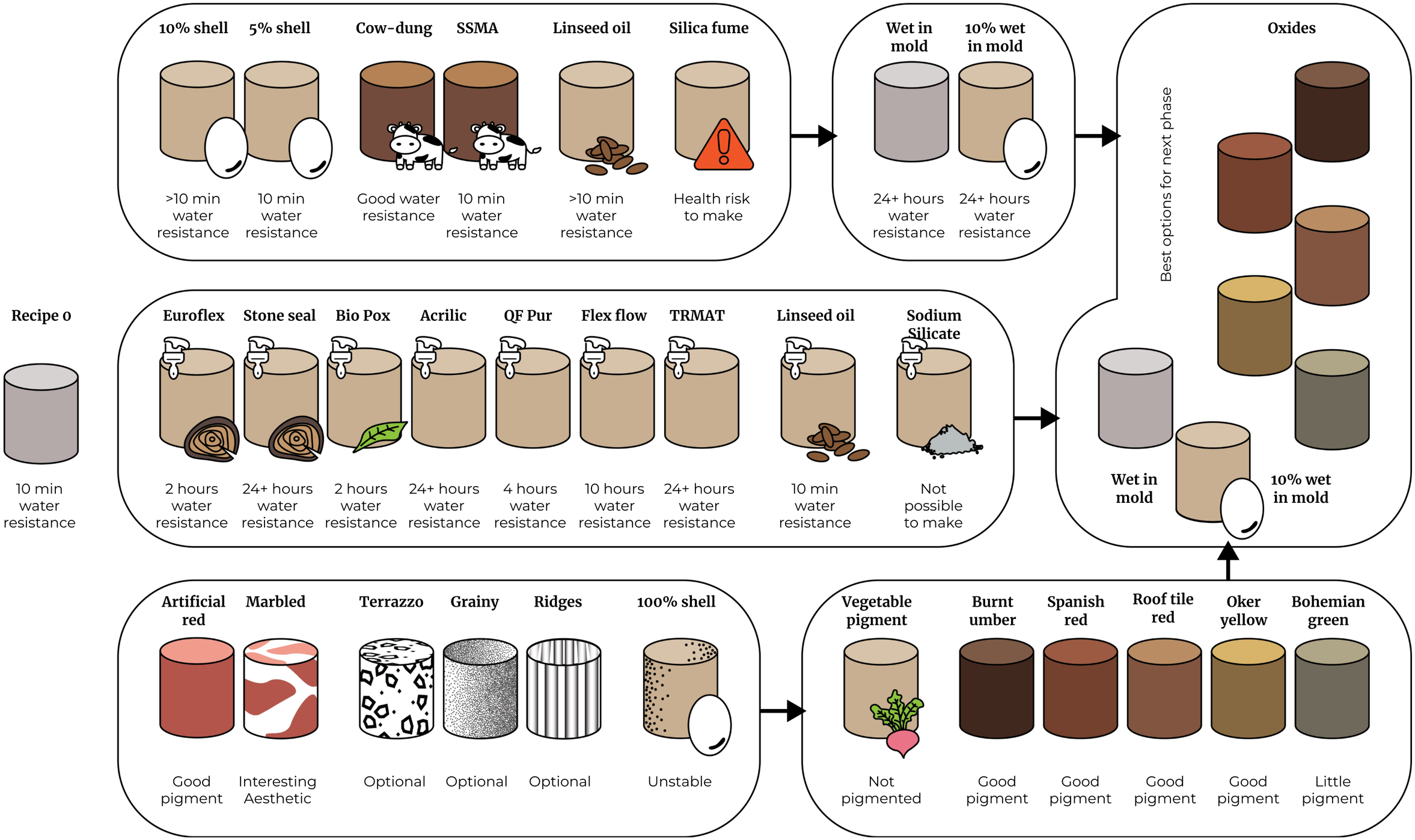


Figure 40 - Tinkering overview.

Tinkering
Summary

This subchapter brings together the main findings from the tinkering phase, in which different strategies to improve CoRncrete's water resistance were tested through small-scale trials and immersion experiments. It does this by addressing the two research questions. Additionally, this subchapter provides an overview of the ingredients and manufacturing approaches explored, and sets out an updated list of requirements and wishes for the material. These outcomes form the basis for the next chapter, where selected options will be developed and assessed in greater depth.

Research question 1
"How can CoRncrete's water resistance be improved to meet architectural needs in wet or humid environments?"

Impershield Stone Seal was selected out of the high-performing sealers due to its bio-based origins and consistent performance. Since this is an off-the-shelf product, further in-depth testing is considered less relevant.

Using eggshells, as 10% sand replacement and pressing before drying, also showed strong potential for increasing water resistance. These options will be the focus of more detailed testing. Different levels of eggshell powder replacement in samples that are pressed before drying, will be the research focus. This way, a balance between the pros and cons of the addition of eggshells can be determined.

Research question 2
"What design characteristics make CoRncrete suitable and desirable for use as a precast architectural block?"

For aesthetics, oxide pigments stood out for their strong coloration and relatively sustainable production, making them the most suitable choice moving forward. Together with the decision to have wall elements as the intended application, this also forms a preliminary answer to the second research question on the material's characteristics as an architectural potential. This intended application is decided on with the knowledge that columns are not often used in the Netherlands and that floor elements are harder to achieve with pre-cast elements. This way, it is possible to determine the materials structural integrity using a compression test.

Requirements & whishes
The following list of requirements and wishes has been gathered throughout this research. Additionally, a number of basic requirements have been added that are both necessary and logical, considering the overarching design goal of this project. Together, these requirements and wishes form a clear framework that aligns with the intended application of CoRncrete as a material for pre-cast load-bearing wall elements.

The relative humidity (RH) percentages and the temperature degrees choices will be explained in the technical characterization chapter. The material should fall within a strength class of at least 13 MPa to function as a load bearing indoor wall (or inner leave of an external wall). This is based on Irish standards for concrete masonry (ACEI Structures Committee, 2022). In the wish list, an RH of 80% is suggested, which simulates a wet or moist sanitary room. This is not a required application for this material, but would be an interesting addition.

Ingredients & manufacture method
For the next chapter, the focus will shift to a more in-depth investigation of the most promising options identified so far. Two main material variations will be carried forward: Recipe 0, pressed while wet, and a 10% eggshell replacement, produced using the same pressing technique. Exploring these two samples side by side will make it

Requirements
CoRncrete must resist an environment with 60% RH and 30 degrees for 24 hours without structural failure.

Must fall within a strength class of at least 13 MPa.

The material must result in lower CO_2 emissions and less energy use than traditional Portland Cement pre-cast concrete.

The product must be designed to allow for easy disassembly and reuse of components.

The material must function within a total wall thickness of max. 40 cm.

The complete wall assembly, including the material, must achieve an R-value of at least 4.7 m^2K/W (Isodirect B.V., 2023).

The cost per unit (brick/block) should be competitive with other sustainable concrete alternatives (e.g., hempcrete blocks, geopolymer blocks), ideally not exceeding their average market price.

The production process should require fewer steps or less specialized labour than rammed earth or bio-cement production.

Wishes
CoRncrete must resist an environment with 80% RH and 30 degrees for 24 hours without structural failure.

Develop a fully circular product with the use of biobased or waste stream materials.

The product should offer a line extension with multiple aesthetic options (e.g., variations in colour or texture).

The complete wall assembly, including the material, must achieve an R-value of 6.7 m^2K/W, suitable for passive houses (Passive House Institute Dr. Wolfgang Feist, n.d.-b).

Tinkering
Summary

possible to balance the strengths and drawbacks of each. Oxide pigments will also be included to refine the aesthetic qualities of the material.

The following images (Figure 41, 42, 43 & 44) give an overview of ingredients and manufacture method that form the base of the following chapters.

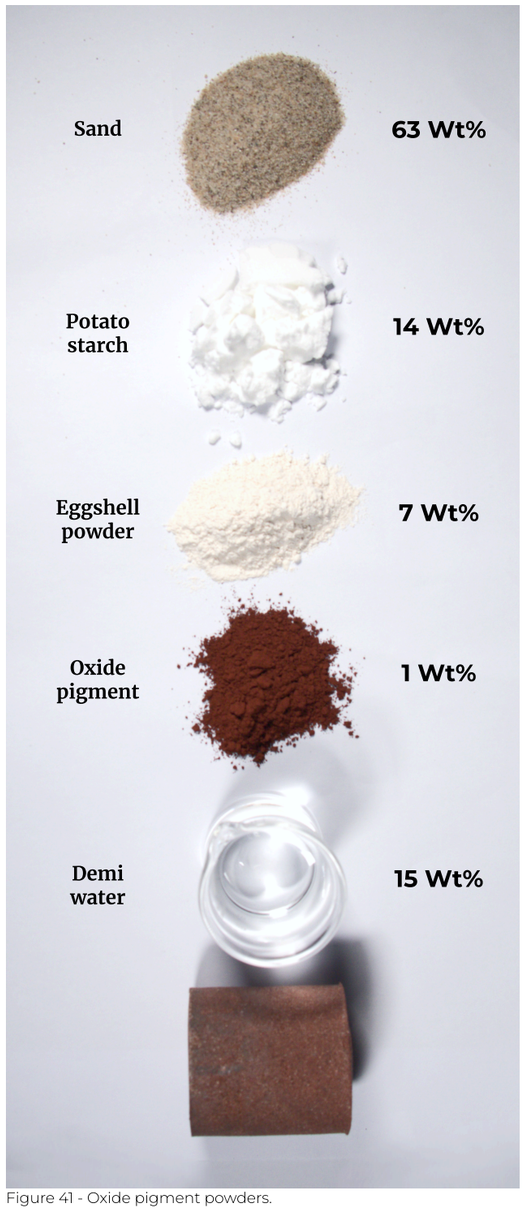


Figure 41 - Oxide pigment powders.

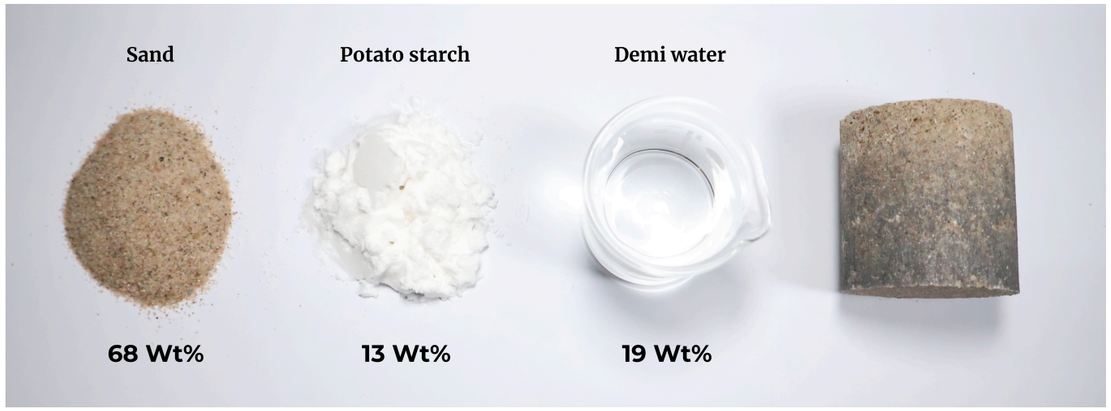
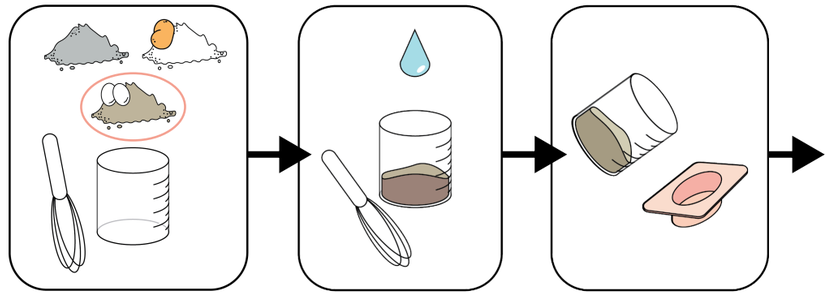


Figure 42 - Ingredient proportions based on weight of recipe 0.



Figure 43 - Ingredient proportions based on weight of 10% eggshell powder sand replacement.



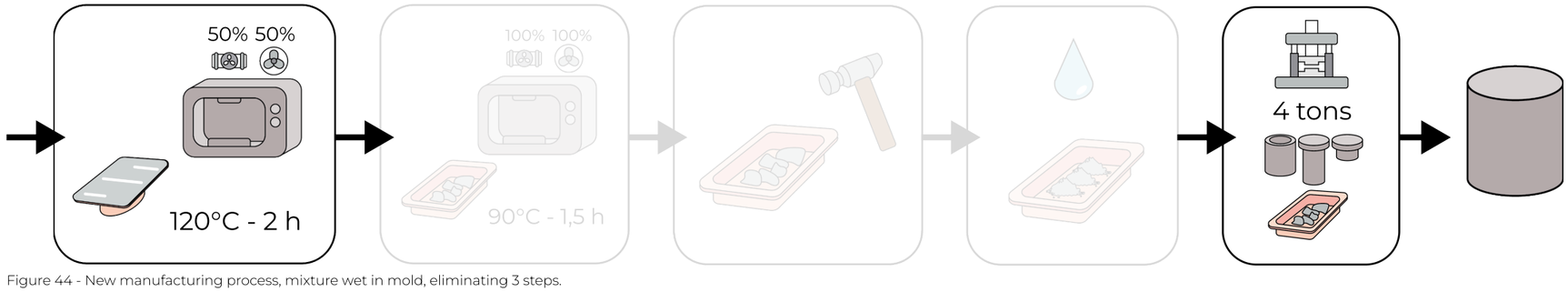


Figure 44 - New manufacturing process, mixture wet in mold, eliminating 3 steps.

Technical

Characterization

5

Characterization
Technical

This chapter presents the technical characterization of CoRncrete through a series of controlled tests. The goal of these tests is to assess the material's mechanical performance and water resistance under different environmental conditions. The chapter first outlines the methodology, including sample preparation, coding, and testing procedures, followed by the results and analysis.

Method

-Test setup climate chamber

To assess the water resistance of this material, three climate scenarios were set up in a Espec SH-661 climate chamber (Figure 45 & 46) to simulate, based on common temperature and humidity assumptions.



Figure 45 - Espec SH-661 climate chamber used in tests.



Figure 46 - Scenario 2 samples in climate chamber.

various realistic but demanding conditions:

- Scenario 1: 4.5 °C and 20% RH — simulating a cold, unheated room in winter.
- Scenario 2: 30 °C and 60% RH — simulating a warm, poorly insulated room in summer.
- Scenario 3: 30 °C and 80% RH — simulating a warm, humid bathroom in summer.

30 °C occurs in poorly insulated rooms during summer (Adaptieve Temperatuurgrenswaarden | TU Delft Repository, z.d.), 4.5 °C represents winter temperatures in unheated spaces (KNMI - Winter 2024-2025 (December, Januari, Februari), z.d.), 20% RH is a feasible value for dry winter conditions (De Gids et al., 2012), 60% RH represents an average indoor humidity level in the Netherlands (KNMI - Vochtigheid, z.d.-c), and 80% RH is assumed for wet spaces such as bathrooms (De Gids et al., 2012).

-Material composition

For these tests, a recipe with 10% sand replacement by ground eggshells (200 µm), while drying after pressing was used, as this showed the best water resistance in previous tests. To investigate the effect of eggshell concentration, additional variants with 7.5% and 12.5% replacement were tested. A recipe without eggshells (recipe 0) served as a reference. Although direct comparison with other studies is challenging due to recipe variations, previous research indicates that 5–15% eggshell replacement can influence moisture resistance (Chong et al., 2020), but that between 5-7% eggshell replacement scored best in compressive strength (Tiong et al., 2020).

-Sample preparation

All samples were cast in cylinders with a diameter of 40 mm (±0,5mm) and a height of 45 mm (±2.8 mm). After mixing, they were cured at ambient temperature in the materials technology laboratory at TU Delft for approximately 6 days. The sample size was 3 per condition. After this curing period, samples were placed in the climate chamber and exposed to one of the scenarios for 24 hours. Immediately after exposure, they were tested for compressive strength to measure their structural integrity directly after humid conditions, without any additional curing. The total time between casting and compressive testing was therefore 7 days and was kept identical for all samples, including the controls that did not undergo moisture exposure in the climate room.

-Compressive strength test

Compressive strength was tested according to ASTM C39/C39M-21 (ASTM International, 2021). This standard specifies a load increase of 0.25 MPa/s with a margin of ±0.05 MPa/s. In my test setup, this force-controlled loading rate was converted into a displacement-controlled rate of 2 mm/min, as also applied in comparable tests by fellow researcher Sam de Haan [source to be added]. The test was performed using a Zwick Z100 material testing machine with a loadcell of a 100 kN (Figure 47 & 48).



Figure 47 - Zwick Z100 material testing machine used in test.



Figure 48 - Sample in Zwick Z100 material testing machine.

-Extra long curing

It became clear from the results that the samples had not yet reached their optimal strength after 7 days of curing. To address this, an additional test was conducted in which all recipes were allowed to cure for 21 days before testing. This supplementary test serves specifically to determine and compare the compressive strength of the different recipes under equal curing conditions and was conducted without additional use of a climate chamber. In contrast, the earlier tests focused on assessing resistance to various climate scenarios.

-Additional submerge tests

To verify earlier findings, an additional water submersion test was carried out with small sample disks (Figure X). This test is intended to confirm whether the different recipes with varying amounts of eggshell powder show the same or similar improvements in water resistance as observed in the preliminary submersion experiment. By repeating this test under controlled conditions, it becomes possible to validate whether the advantage of eggshell addition is consistent across the different concentrations. These samples cured for 1.5 weeks.

Additionally, the usual cylinder samples were submerged for 24 hours (previously tested submerge time), dried and tested for compressive strength. The samples were dried in the oven at 100 degrees (100% flap & fan) for 1 hour the day before the compression tests. A reference sample of each recipe is also tested for compression without being submerged before. These samples cured for 2 weeks.

Both tests were carried out in reaction to results of the climate chamber tests and were done with leftover samples. These samples were the 3 variations of eggshell sand replacement and, for the second submerge test, a wet in mold recipe 0 sample.

-Sample identification

To clearly identify and organize all samples, a two-symbol coding system was used, combining the recipe type and the climate scenario:

Recipe codes:

- O = 0% eggshells (reference)
- A = 7.5% eggshell replacement
- B = 10% eggshell replacement
- C = 12.5% eggshell replacement

Climate scenario codes:

- – = No climate exposure (reference)
- D = 5 °C, 20% RH
- H = 30 °C, 60% RH
- P = 30 °C, 80% RH

This way, each sample receives a two-character code. For example, B– refers to a 10% eggshell sample that was not exposed to climate conditions (control), while CH refers to a 12.5% eggshell sample tested at 30 °C and 60% RH.

For the additional tests, extra codes were created. Extra long curing uses the scenario code "E", resulting in code names such as EO and EA. For the second water submerge test, the wet in mold recipe 0 sample was coded with a O, and the eggshell samples with their percentage sand replacement (7.5, 10, 12.5).

-Data collection & analysis

The load–displacement data obtained from the compression tests were processed in Excel to derive stress–strain curves for each sample. Stress was calculated by dividing the applied load by the cross-sectional area

Characterization
Technical

of the specimen, while strain was calculated as the measured deformation relative to the original height of the sample after 24 hours in the climate room. Plotting stress against strain provided a curve that describes the mechanical response of the material under compressive load.

From these curves, multiple mechanical properties were extracted:

- Elastic modulus (E, GPa): determined from the slope of the linear-elastic portion of the stress–strain curve, representing the stiffness of the material.
- Yield strength (YS, MPa): defined as the stress level where permanent (plastic) deformation begins. This was identified using the 0.2% offset method, where a line parallel to the elastic modulus is drawn from 0.2% strain and its intersection with the curve marks the yield point.
- Ultimate compressive strength (UCS, MPa): the maximum stress value reached on the curve before failure, representing the peak load-bearing capacity of the sample.
- Deformation at failure (%): the total strain recorded at the point of fracture or collapse.
- Toughness (J/m^3, optional): approximated as the area under the stress–strain curve, reflecting the energy absorbed by the material before failure.

For each sample group (n = 3), mean values and standard deviations were calculated to represent the mechanical properties of a given recipe under a given condition. This approach enabled comparisons across different formulations and climate exposures, as well as an assessment of variability within each group.

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Technical

Results
-Climate scenario -

Within the samples in climate scenario -(n=3), the samples without eggshell powder (-O in Figure 51) show the highest UCS of 11.02 MPa, with a standard deviation of 1.21. Between the samples with eggshell powder (-A in Figure 49, -B in Figure 52, and -C in Figure 50), -A has the highest UCS of 5.31 MPa, followed by -B with an UCS of 4.23 MPa and -C with the lowest UCS of 1.36 MPa. These UCS averages show a standard deviation of 0.83, 0.38 and 0.42 respectively. (Figure 53)

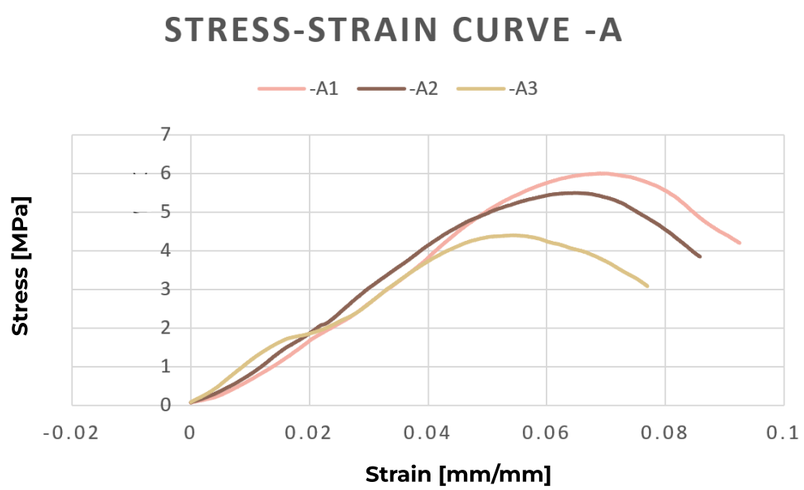


Figure 49 - Stress-Strain curve showing n=3 of -A samples.

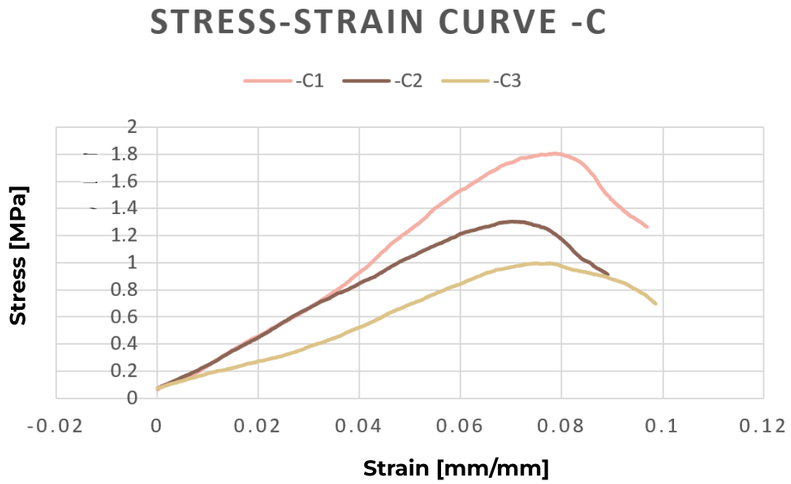


Figure 50 - Stress-Strain curve showing n=3 of -C samples.

Figure 51 - Stress-Strain curve showing n=3 of -O samples.

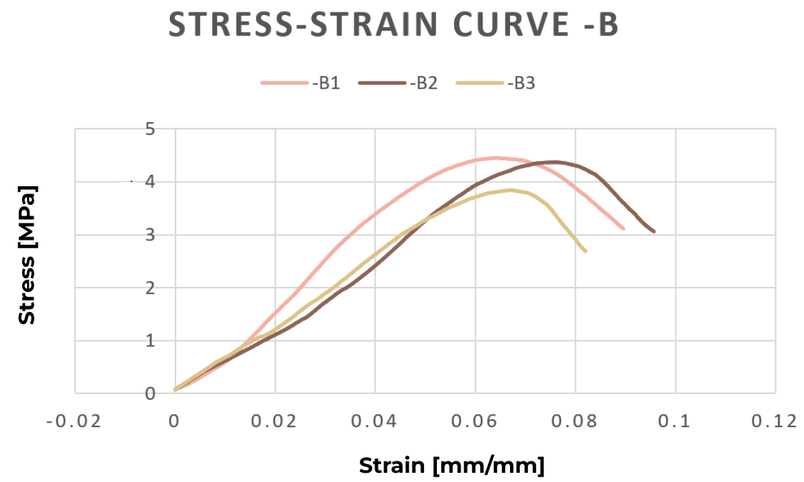


Figure 52 - Stress-Strain curve showing n=3 of -B samples.

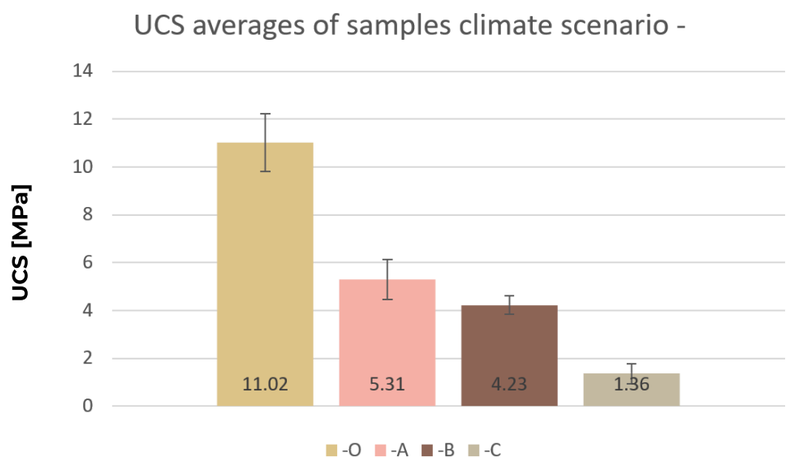


Figure 53 - UCS averages of samples climate scenario -.

Characterization
Technical

-Climate scenario D

Within the samples in climate scenario D (n=3), the samples without eggshell powder (DO in Figure 56) again show the highest UCS of 12.29 MPa, with a standard deviation of 1.97. Between the samples with eggshell powder (DA in Figure 54, DB in Figure 57, and DC in Figure 55), DA has the highest UCS of 4.48 MPa, followed by DC with an UCS of 3.82 MPa and DB with the lowest UCS of 2.77 MPa. These UCS averages show a standard deviation of 0.98, 0.38 and 0.38 respectively. (Figure 58)

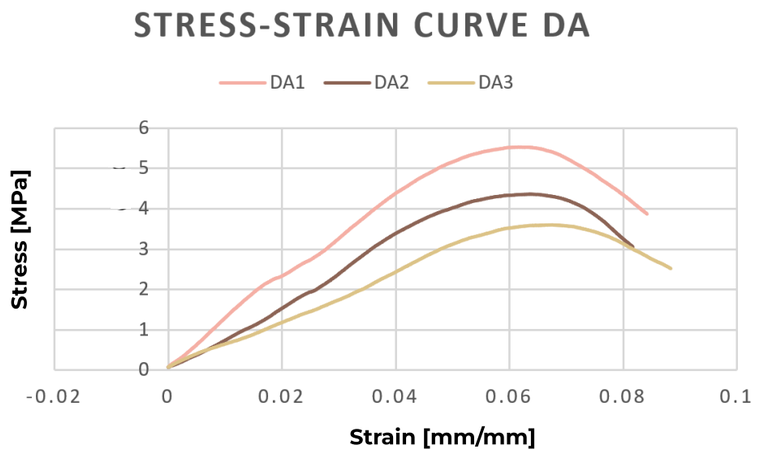


Figure 54 - Stress-Strain curve showing n=3 of DA samples.

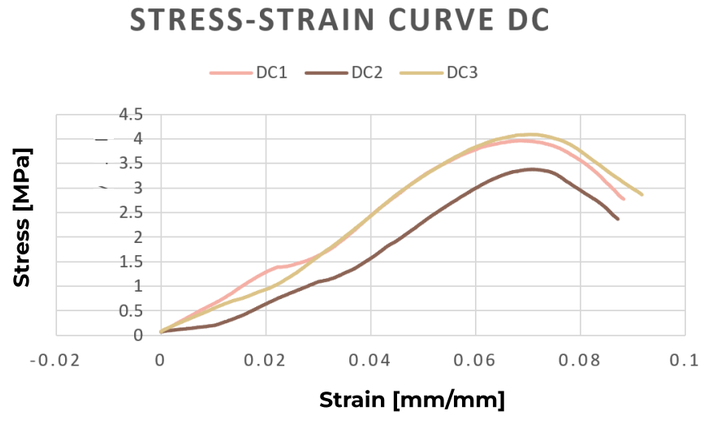


Figure 55 - Stress-Strain curve showing n=3 of DC samples.

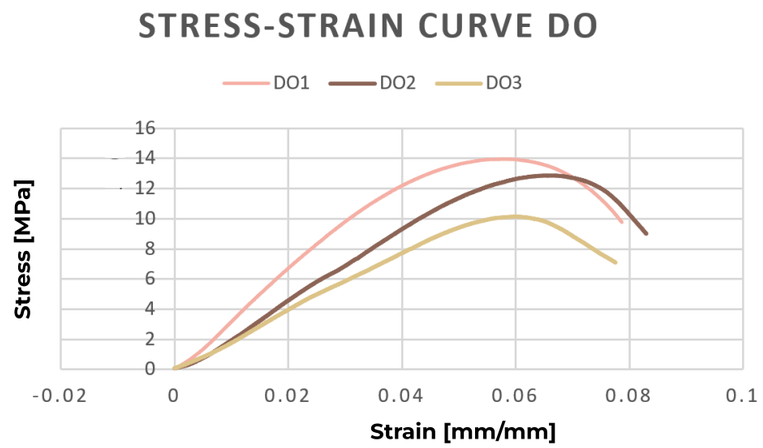


Figure 56 - Stress-Strain curve showing n=3 of DO samples.

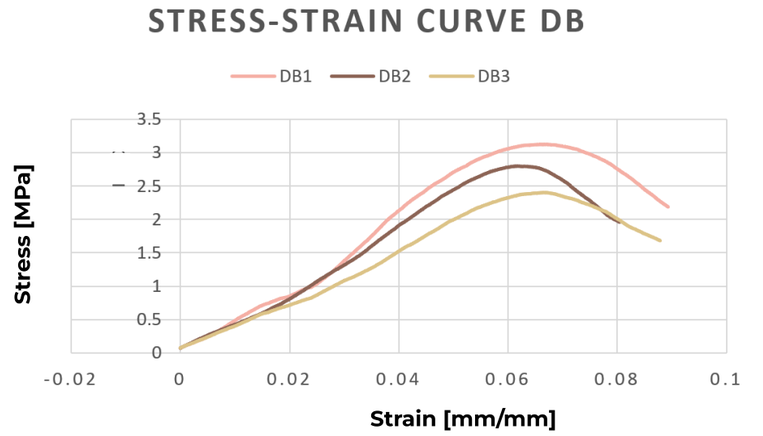


Figure 57 - Stress-Strain curve showing n=3 of DB samples.

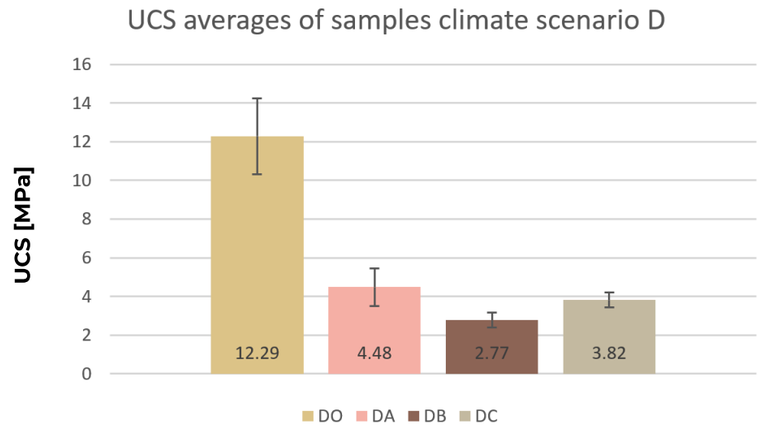


Figure 58 - UCS averages of samples climate scenario D.

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Technical

-Climate scenario H

Within the samples in climate scenario H (n=3), the samples without eggshell powder (HO in Figure 61) again show the highest UCS of 12.99 MPa, with a standard deviation of 1.36. Between the samples with eggshell powder (HA in Figure 59, HB in Figure 62, and HC in Figure 60), HA has the highest UCS of 5.43 MPa, followed by HB with an UCS of 4.63 MPa and HC with the lowest UCS of 4.64 MPa. These UCS averages show a standard deviation of 0.99, 1.43 and 0.52 respectively. (Figure 63)

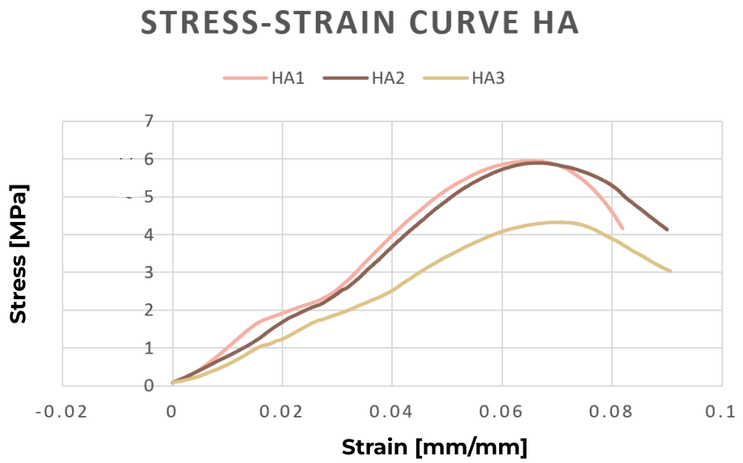


Figure 59 - Stress-Strain curve showing n=3 of HA samples.

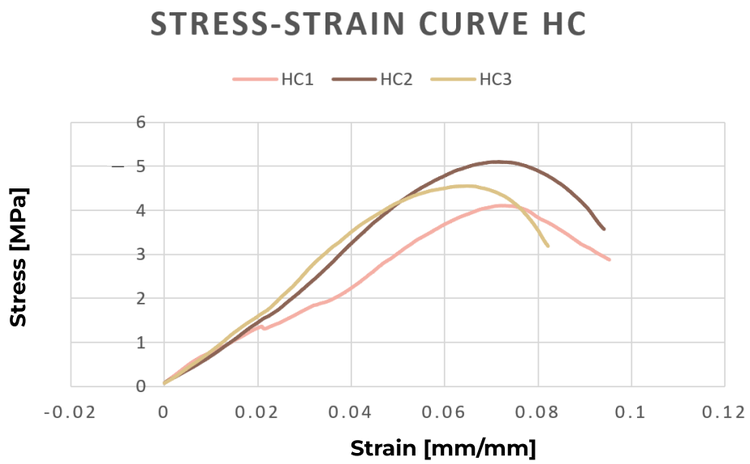


Figure 60 - Stress-Strain curve showing n=3 of HC samples.

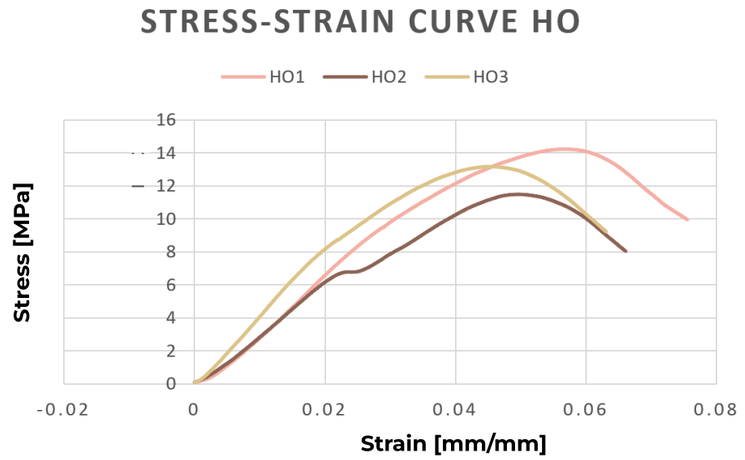


Figure 61 - Stress-Strain curve showing n=3 of HO samples.

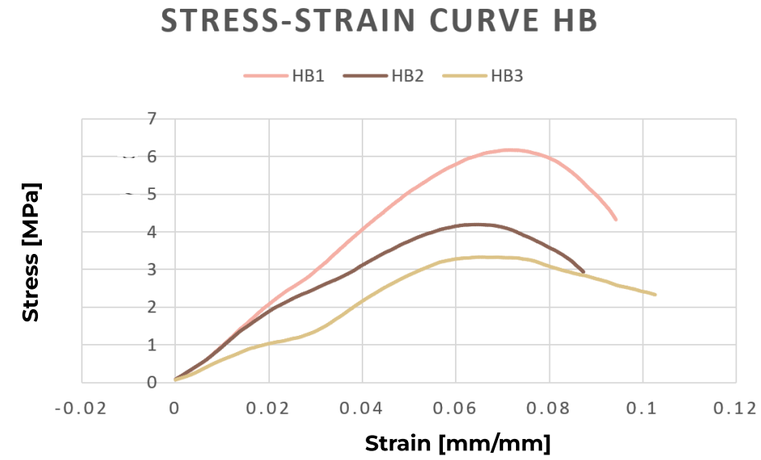


Figure 62 - Stress-Strain curve showing n=3 of HB samples.

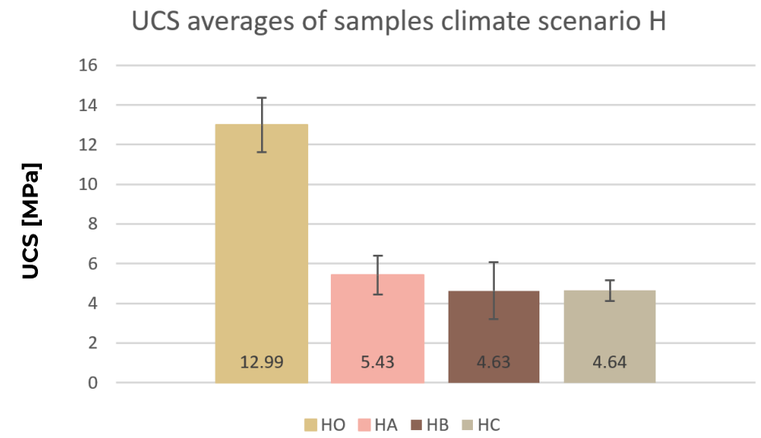


Figure 63 - UCS averages of samples climate scenario H.

Characterization
Technical

-Climate scenario P

Within the samples in climate scenario P (n=3), the samples without eggshell powder (PO in Figure 66), just like in the previous 3 climate scenario's, show the highest UCS of 10.21 MPa, with a standard deviation of 0.24. Between the samples with eggshell powder (PA in Figure 64, PB in Figure 67, and PC in Figure 65), PC has the highest UCS of 5.56 MPa, followed by HB with an UCS of 4.98 MPa and PA with the lowest UCS of 4.72 MPa. These UCS averages show a standard deviation of 1.78, 0.55 and 0.49 respectively. (Figure 68)

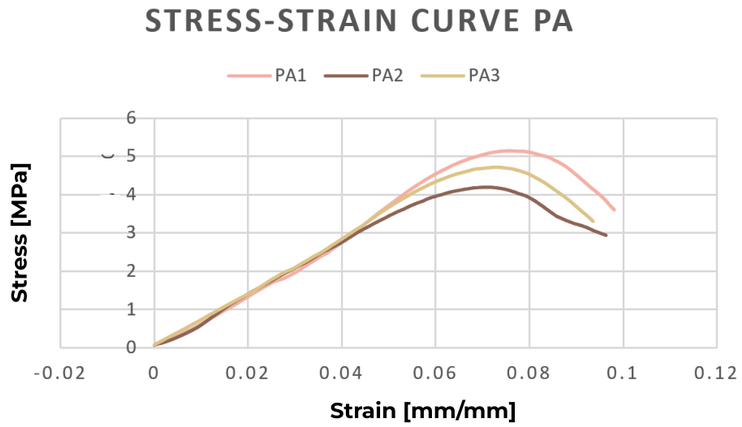


Figure 64 - Stress-Strain curve showing n=3 of PA samples.

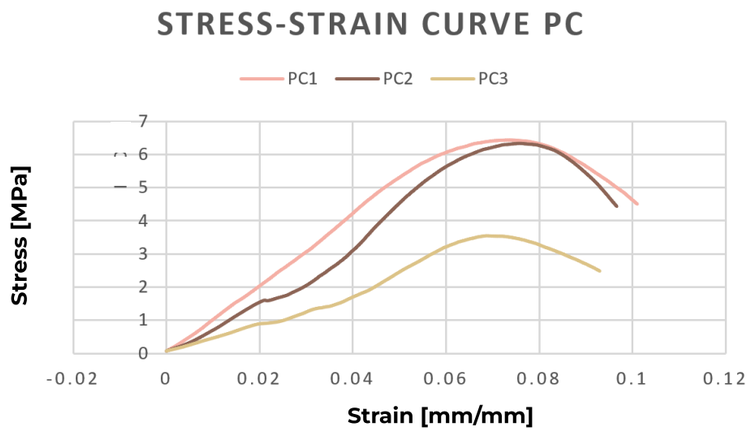


Figure 65 - Stress-Strain curve showing n=3 of PC samples.

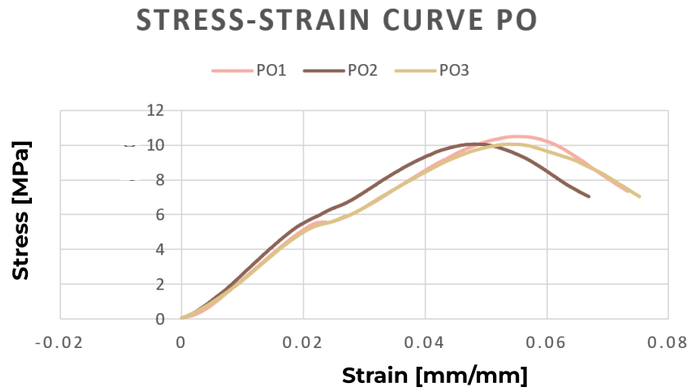


Figure 66 - Stress-Strain curve showing n=3 of PO samples.

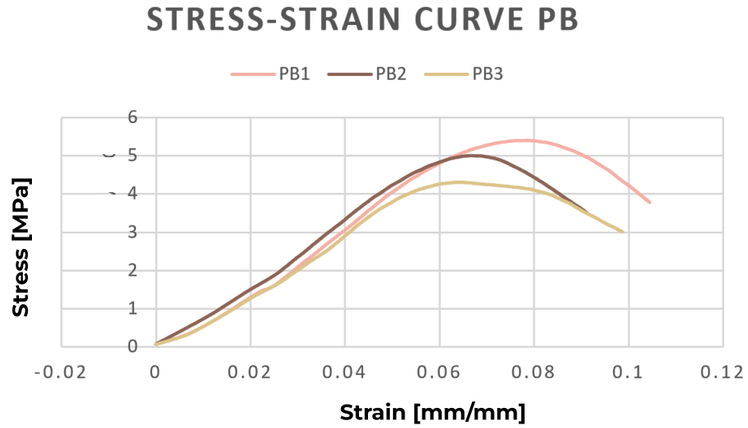


Figure 67 - Stress-Strain curve showing n=3 of PB samples.

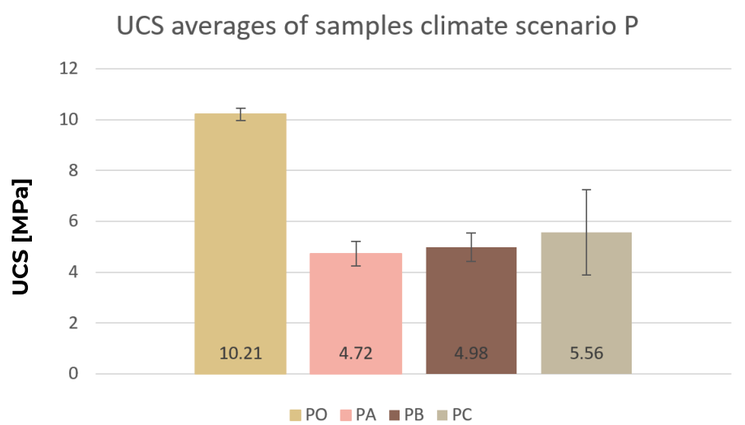


Figure 68 - UCS averages of samples climate scenario P.

Characterization
Technical

-Across climate chamber scenario's
In all climate chamber scenario's (n=3), control sample O had the highest UCS with strengths ranging between averages of 10.21 MPa and 12.99 MPa with the highest strength being in climate scenario H and the lowest in climate scenario P (Figure 71). Samples A had similar UCS's across climate scenario's, ranging from 4.48 MPa in climate scenario D to 5.43 MPa in climate scenario H (Figure 69). Samples B showed more variation across climate scenario's with UCS's ranging from 2.77 MPa in climate scenario D to 4.98 MPa in climate scenario P (Figure 72). Finally, samples C showed the highest variation across climate scenario's with UCS's ranging from 1.36 MPa in climate scenario - to 5.56 MPa in climate scenario P (Figure 70).

Some STD's (standard deviation) stand out. for multiple UCS numbers, the SD is quite high. DO has a STD of 1.97 and PC has a STD of 1.78. Other STD's for UCS vary between 0.24 and 1.43. (Appendix A)

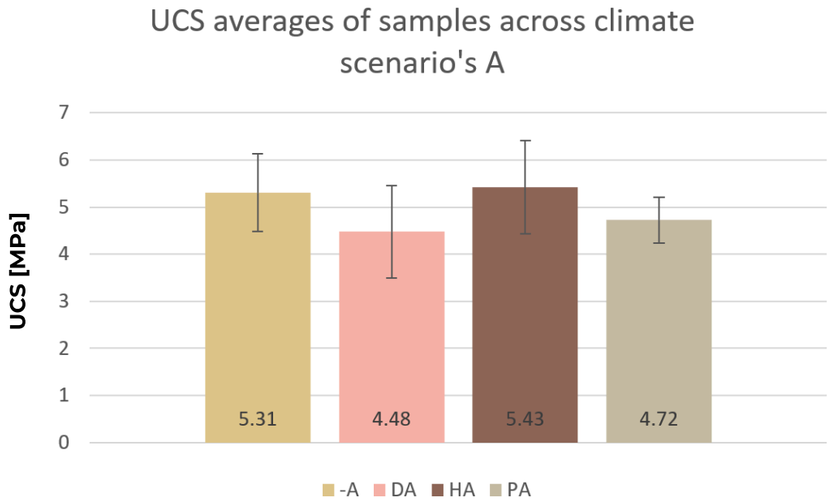


Figure 69 - UCS averages of samples across climate scenario's A.

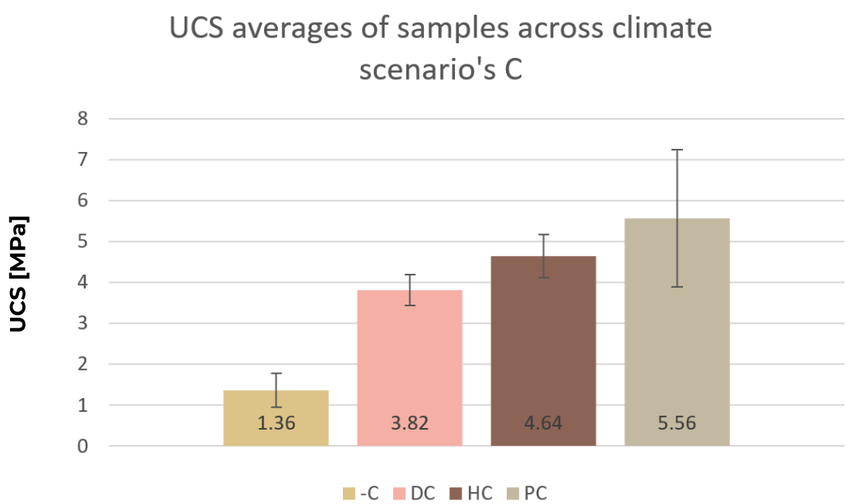


Figure 70 - UCS averages of samples across climate scenario's C.

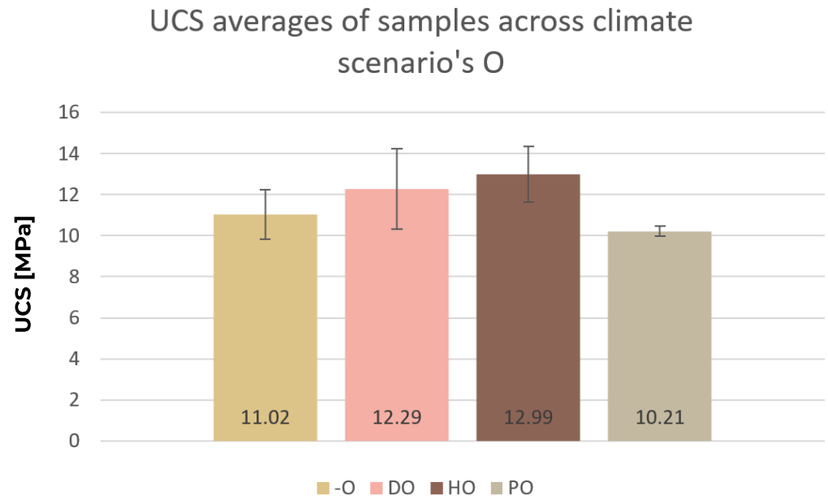


Figure 71 - UCS averages of samples across climate scenario's O.

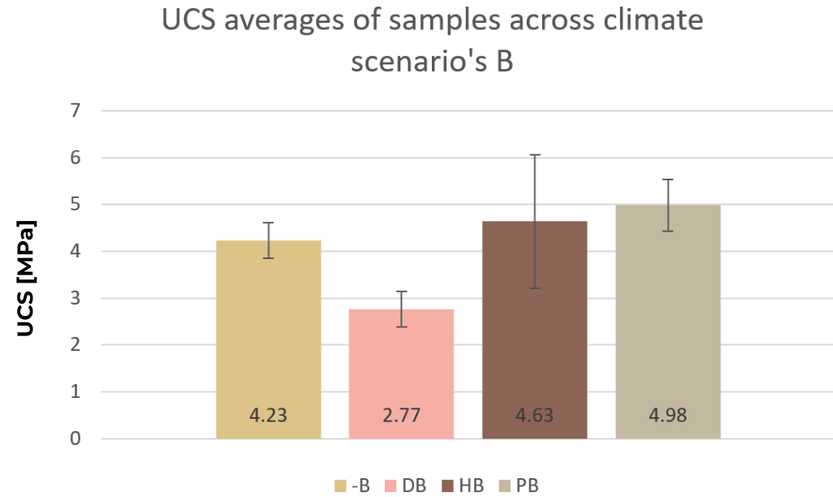


Figure 72 - UCS averages of samples across climate scenario's B.

Characterization
Technical

-Extra long curing
The extra curing tests (n=3) show consistent improvements in mechanical properties across all four recipes, compared to samples that cured for only 7 days.

UCS reached its maximum in EC (13.97 MPa, STD 0.92) (Figure 74), followed by EO (12.98 MPa, STD 1.29) (Figure 75), EB (12.93 MPa, STD 1.51) (Figure 76), and EA (12.26 MPa, STD 1.83) (Figure 73). Standard deviation was lowest in EC and highest in EA and EB, suggesting more consistency in the EC results. (Figure 77)

Overall, EC (12.5% eggshell replacement) achieved the highest strength values for UCS with the lowest variation. EA tended to perform weakest overall, with higher variation in results.

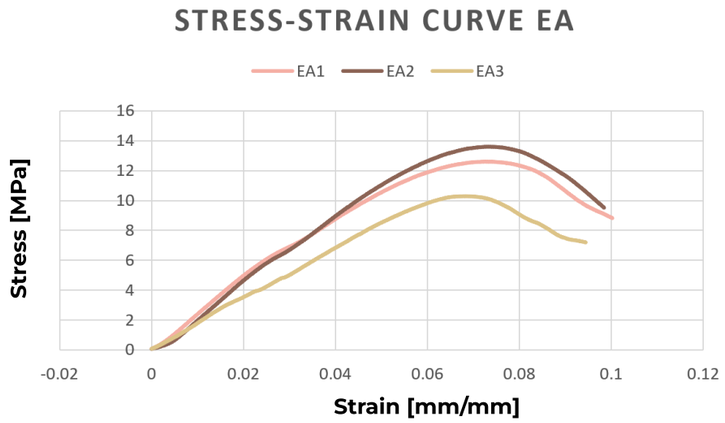


Figure 73 - Stress-Strain curve showing n=3 of EA samples.

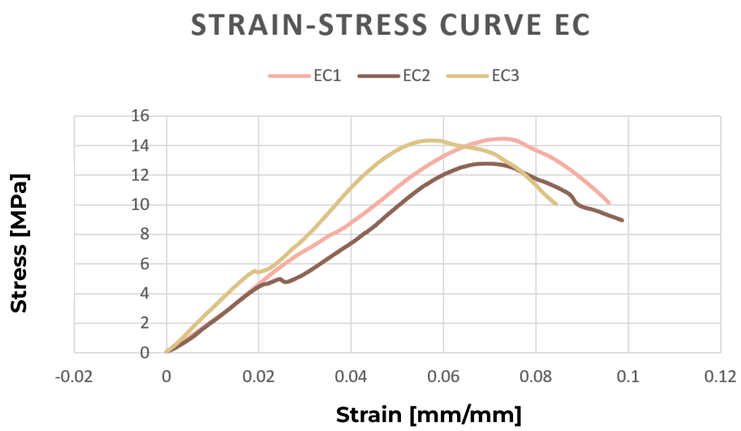


Figure 74 - Stress-Strain curve showing n=3 of EC samples.

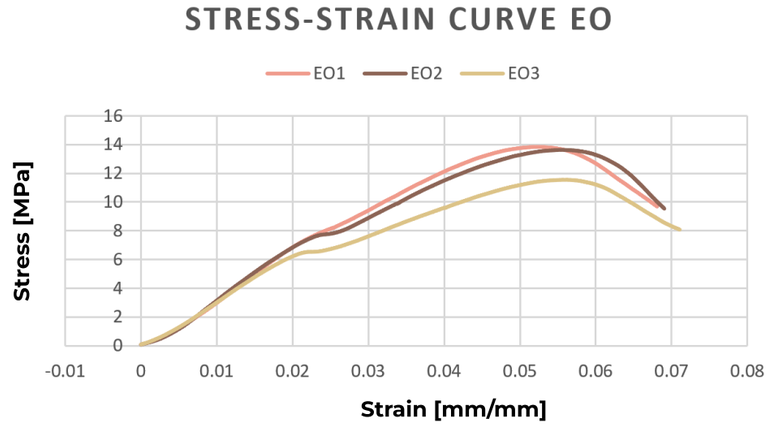


Figure 75 - Stress-Strain curve showing n=3 of EO samples.

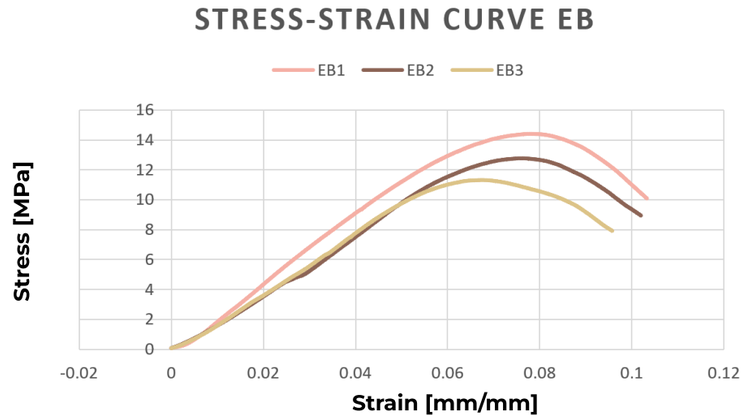


Figure 76 - Stress-Strain curve showing n=3 of EB samples.

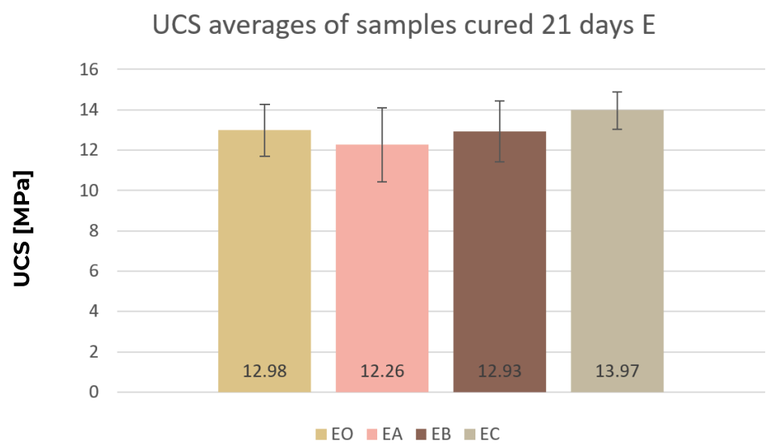


Figure 77 - UCS averages of samples cured for 21 days E.

Characterization
Technical

-Additional submerge tests 1
The initial water submerge test, using small disks (n=1), showed that all 3 samples survived for at least 24 hours in water.

-Additional submerge tests 2
The second water submerge tests (n=1) compared samples tested in their initial state (“-1”) to those immersed in water for 24 hours and subsequently dried (“-2”). Elastic modulus showed strong reductions after immersion.

UCS showed strong reductions after submersion. Where O-1 measured 10.96 MPa, it reduced to 2.84 MPa in O-2 (−74%) (Figure 78). For 7.5%, UCS dropped from 6.35 MPa to 0.48 MPa (−92%) (Figure 81). The 10% sample fell from 9.89 MPa to 1.31 MPa (−87%) (Figure 79). The 12.5% sample decreased from 8.62 MPa to 0.83 MPa (−90%) (Figure 82). Sample O had the lowest reduction in strength compared to the samples with eggshell powder additions (Figure 80 & 83)

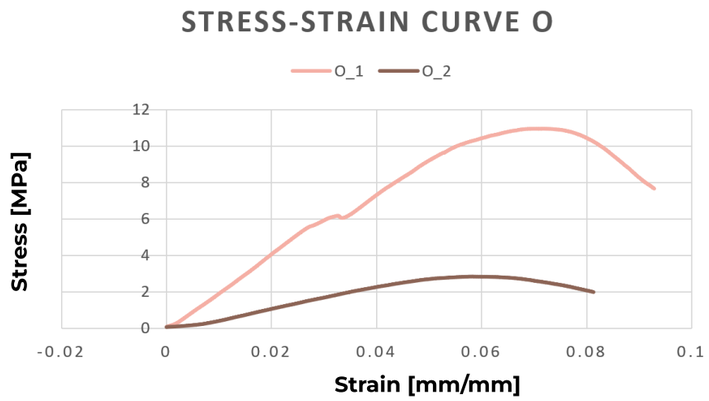


Figure 78 - Stress-Strain curve sample O dry (O_1) and after 24 hour submerged (O_2).

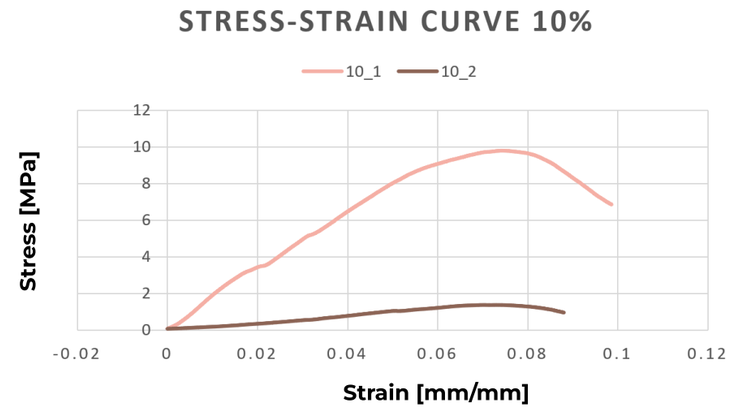


Figure 79 - Stress-Strain curve sample 10% dry (10_1) and after 24 hour submerged (10_2).

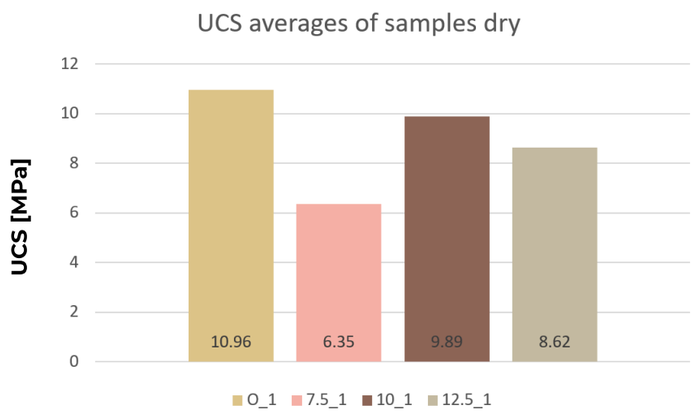


Figure 80 - UCS averages of samples dry.

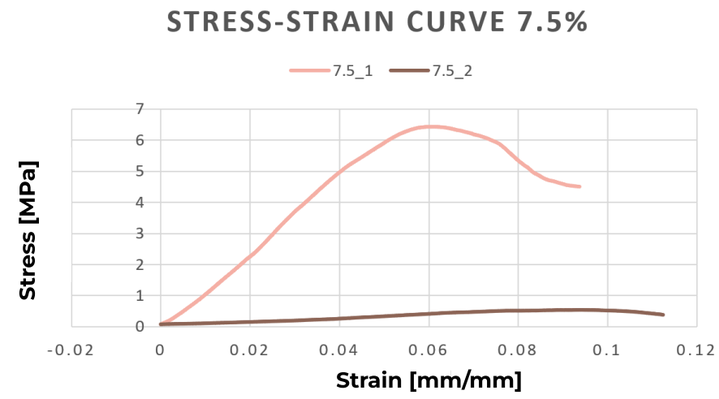


Figure 81 - Stress-Strain curve sample 7.5% dry (7.5_1) and after 24 hour submerged (7.5_2).

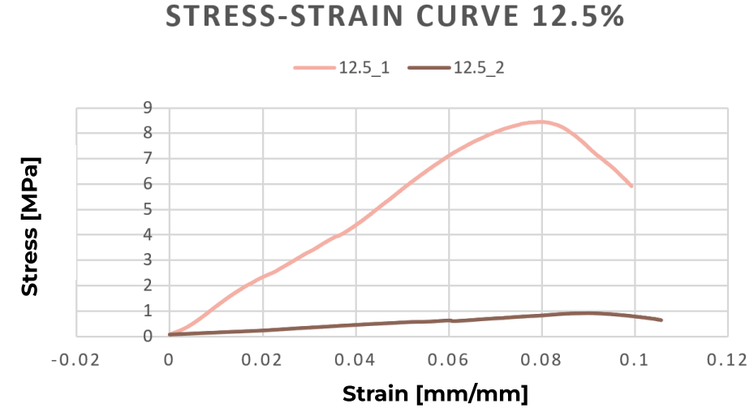


Figure 82 - Stress-Strain curve sample 12.5% dry (12.5_1) and after 24 hour submerged (12.5_2).

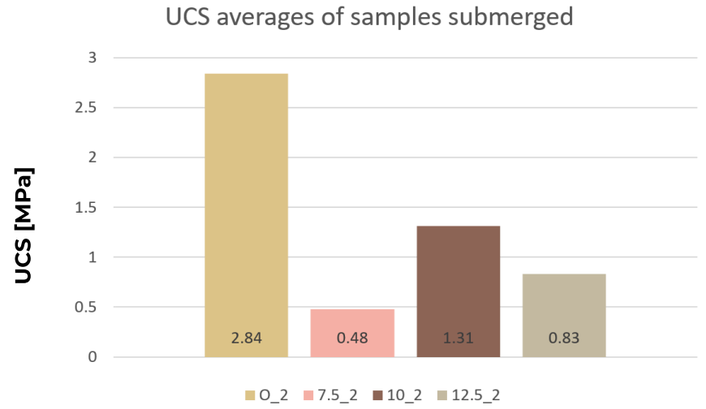


Figure 83 - UCS averages of samples submerged for 24 hours.

Characterization
Technical

Conclusion

-water resistance

The results in the climate chamber are assumed to not be reliable when trying to compare different climate room settings. Although some sample show a higher average, in for example UCS, it is hard to make conclusions due to high STD's and the assumption that the samples had not cured long enough to get to full strength. With the possibilities of many varying moisture levels in the samples during compression tests, the variables are to high to make any conclusions.

With the additional water submerge tests, more assumptions were made about the samples. The first submerge test showed 3 samples that performed similarly in water. Some dissolved more than others, but it is believed not enough of a difference to assume different performances throughout the levels of eggshell sand replacement. The second submerge test, again, showed a lot of similarity among the samples. All samples, including the wet in mold recipe 0 sample, had high reductions in strength and elastic modulus. Some samples had lower initial strengths, but this could be related to damages and imperfections in some of the samples, resulting in weaker samples.

It is assumed that the different levels of eggshell sand replacement and the wet in mold recipe 0, do not differ significantly and can all be evenly considered as best options concluding this research.

Although the decrease in strength is high when exposed to water for a long period, the samples did not fully dissolve in the water, showing an increase in water resistance. It is also generally not required for a material withstand such harsh conditions.

-Strength

Although sample EC showed the highest UCS, all samples displayed similar strength results. EC's value of 13.97 MPa was accompanied by a lower STD (0.92) compared to the other samples (1.29–1.83). This indicates that the average is based on multiple measurements with relatively high strength, suggesting that sample EC may consistently achieve a UCS close to 13.97 MPa.

For the final design, a block with at least 13.5 MPa compressive strength was required. Sample EC is the only one that meets this threshold, although it does so with only a slight margin. It is therefore assumed that EC would be the best candidate, but additional measures may need to be taken to ensure the block reliably reaches the required strength.

This suggests that, based on the results, the sample with 12.5% eggshell sand replacement could potentially be the best-performing option among those tested.

Discussion

-Geometry

The top and bottom surfaces of the samples were not perfectly parallel or flat which might have influenced the materials behavior in the compression test. Within the time frame and with the equipment available during this project, it was not possible to fully correct this. In future research, a lathe could be considered, although sand-based mixtures are unsuitable for such machines as they damage the blades. Alternatively, a custom setup using a sanding technique could be developed to ensure parallel and flat surfaces.

-Pressing technique

The pressing method used required intermediate compaction of the mixture. This step created a separation between layers of the mix, occasionally leading to cracks or irregularities in stress–strain behavior, such as small dips in the curve. It is expected that further process development will make it possible to manufacture samples with a single pressing step, combined with a precise dosing of material, which would eliminate this issue.

-Used compression standard

The compressive strength tests followed ASTM standards for concrete, as the study aimed to benchmark the material against conventional concrete. However, analysis of the stress–strain curves showed that the samples behaved differently from concrete. Where concrete usually shows a rounded curve (Figure 84), the samples in this research show a more linear progression in the graph (Figure 85). This suggests that, in the future, alternative standards more suited to the mechanical behavior of bio-based composites should be considered.

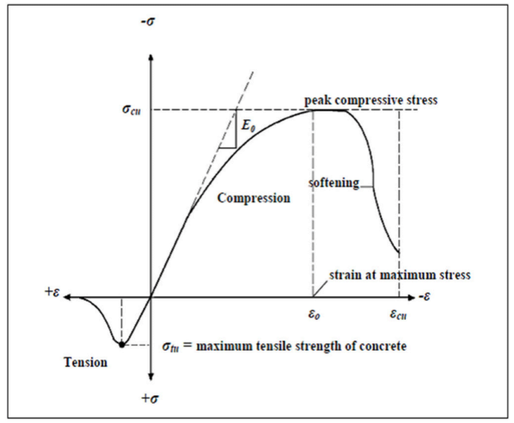


Figure 84 - Traditional concrete stress-strain curve (Figure 4: Typical Stress-strain Curve for Concrete [45], n.d.).

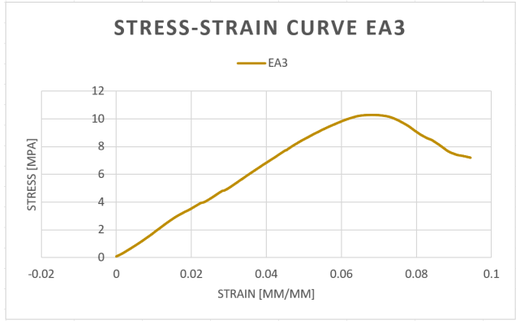


Figure 85 - Example of linear progression in stress-strain curve of compression testing on CorNcrete samples.

-Duration climate chamber

Due to project time limitations, the water-resistance tests in the climate chamber were limited to 24 hours of exposure. In literature, a minimum of seven days is often applied to assess moisture resistance more reliably. This shorter duration may have made the results less robust and could underestimate long-term performance.

-Amount of samples

For practical reasons, a sample size of three was used per condition. While this provided indicative results, a larger sample size would be necessary in future studies to reduce variability and improve statistical reliability.

-Mold and drying effects

During drying, mold occasionally developed on the samples when wet sections were left without ventilation for too long. This was later mitigated by regularly rotating the samples during curing, but the presence of mold may have altered material properties in some cases. Additionally, cracks were observed in various samples, either immediately after pressing or during drying. These cracks could negatively affect both mechanical strength and water resistance.

-Variable moisture content

Samples tested after one week of curing were not fully dry. During this stage, it was assumed that variations in moisture content exist. This likely happened due to differences in the initial wetness of the mix coming out of the oven and the use of different types and sizes of silicone molds. Such variations may have influenced both compressive strength and water-resistance results.

-Dissolving of starch

An explanation for the sharp reduction in UCS after water immersion could be that the starch binder partially dissolves when exposed to water. If parts of the binder are lost from the sample, the internal cohesion of the material decreases, resulting in significantly lower compressive strength. This might explain why the immersed samples perform notably worse compared to their dry counterparts. Further testing is required to confirm whether starch dissolution is indeed the primary cause of this reduction.

-Manual pressing procedure

All samples were pressed using a hydraulic press that required manual operation. The pressure had to be applied by hand until the desired level was reached, which was

Characterization
Technical

only visible on a gauge. This method introduced small variations between samples, as it was difficult to achieve identical pressure levels with complete precision. For the same reason, it was also not possible to identify the exact amount of pressure applied. An automated press could eliminate this source of variability and provide more consistent results

-Varying sample sizes and densities
Due to a non-automised manufacture procedure in the lab, varying amounts of mixture went into the oven. Together with the varying amount of pressure reached in the hydraulic press, the samples had minor differences in them. Some were a bit taller or shorter and there were differences in the densities of the samples. Due to the differences in the samples, the amount of variations increased during the tests. These variations should be considered when interpreting the results.

-Longer drying of samples
The samples in these test were tested on compressive strength after 7 or 21 days of drying. When following standard procedures for testing concrete samples, drying times of 3, 7, 28 and 30 days are considered for indication of the compressive strength (ASTM International, 2021). To properly assess the UCS of the samples in this report, an additional test should be conducted where the samples are dried for 28 and maybe 30 days. This could result in even higher compressive strengths than currently measured

-low elastic modulus
The measured elastic modulus of the samples after 21 days of curing (Appendix X) was already relatively low. However, the values obtained from the samples that had cured for only seven days were generally much lower. This difference is most likely related to the shorter curing period, which may have prevented the material from developing its full stiffness.

A low elastic modulus is usually associated with high elasticity with for example materials like rubber. For reference, lightweight structural concrete typically shows an elastic modulus of 11–21 GPa, whereas rubber has a modulus of only 0.0012–0.0021 GPa, roughly a thousand times smaller. (Ansys, 2021)

When comparing the present results with other materials, the CoRncrete samples with the lowest modulus were close to cork board (0.010–0.013 GPa), while the highest values were comparable to cedar wood (0.28–0.30 GPa). Most samples that cured for 21 days, either with or without eggshell powder additions, have a similar elastic modulus as Sedar wood. The structural integrity of this general elastic modulus value for CoRncrete should be investigated on structural integrity. (Ansys, 2021)

Summary
This chapter focused on the technical characterization of CoRncrete, with the aim of assessing its compressive strength and water resistance under controlled conditions. Samples with varying levels of eggshell sand replacement (0%, 7.5%, 10%, and 12.5%) were prepared and tested in climate chamber scenarios, additional curing periods, and water submersion setups. Data on strength, deformation, and stiffness were collected and analyzed to evaluate the role of eggshell content and curing time.

-Results
The climate chamber tests showed that all samples were highly sensitive to curing time and moisture exposure, making results between scenarios difficult to compare due to large variability. Extra curing (21 days) improved strength across all recipes, with the 12.5% eggshell variant (EC) achieving the highest and most consistent compressive strength (UCS 13.97 MPa). Additional water submersion tests confirmed that, while all recipes lost significant strength after immersion, none of the samples dissolved fully, demonstrating improved water resistance compared to earlier iterations. Differences between the eggshell concentrations were small, suggesting similar performance across the range tested.

-Conclusion
The findings indicate that eggshell additions do not drastically change moisture resistance, but the 12.5% variant stands out as the most reliable in terms of compressive strength, meeting the minimum design requirement of 13.5 MPa. Overall, CoRncrete with eggshell powder can withstand short-term water exposure and reach sufficient strength with adequate curing, making it a promising candidate for further development as a sustainable cement-free material.



Experiential

Characterization 6

Characterization
Experiential

While technical characterization provides measurable data on the mechanical and physical properties of CoRncrete, understanding how the material is experienced by its intended users is equally important. As CoRncrete is envisioned for use in pre-cast load-bearing wall elements, its success depends not only on structural performance but also on its aesthetic and experiential appeal, which directly relates to Research Question 2.

This chapter explores CoRncrete through the lens of experiential characterization, using the Material Driven Design (MDD) Experiential Characterization toolkit developed by the Materials Experience Lab (Karana et al., 2015). This approach recognizes that materials influence product experience on four interconnected levels: sensorial, interpretive, affective, and performative. By assessing CoRncrete across these dimensions, we gain insights into how architects and other stakeholders might perceive, interpret, and value the material in architectural applications.

Method

The Material Driven Design Experiential Characterization toolkit was used to facilitate structured, participant-centered sessions. Each session lasted approximately 30 minutes and involved one participant. Participants were given three different samples of CoRncrete:

1. Plain - A sample with eggshell powder.
2. Marbled - A sample with eggshell powder and a marbled aesthetic.
3. Pigmented - A sample with eggshell powder and Spanish red oxide (because of clear pigmentation)

The samples were presented in a randomized order, different for each participant, to minimize order bias.

The toolkit guides participants through the four experiential levels:

- Performative level (actions): Observations were made on how the material invites or restricts certain actions, such as how it feels to hold, manipulate, or interact with.
- Sensorial level (haptic feel): Participants assessed sensory characteristics such as texture, weight, and temperature.
- Interpretive level (associations): Participants reflected on the meanings or associations the material evoked, supported by a list of interpretive words as inspiration.
- Affective level (emotions): Participants described their emotional responses, aided by a list of affective words provided during the session.

For the sensorial level, data was collected using a structured questionnaire to facilitate easy data structures and later evaluation. They had to rank the sample given in certain sensory attributes (for example how hard or soft). They did this by ranking the sample between a -2 and a 2, symbolizing either hard or soft in this example. The interpretive and affective levels were explored through open discussion, with participants mapping their thoughts and emotions using the toolkit's participant's map. The performative level was assessed throughout the whole test by observation and revising video footage.

In addition to evaluating the three selected samples, participants were also asked to compare recipe 0 (the reference without eggshell powder) with the eggshell-based recipe. This comparison provided insights into whether the inclusion of eggshells influenced the perception of the material beyond its technical benefits. Furthermore, participants were invited to reflect on the entire line extension of oxide-based colors, sharing their preferences and impressions across the different aesthetic options. These reflections gave a broader perspective on how CoRncrete could be positioned both as a sustainable material and as a versatile design product.

These sessions were carried out with participants familiar with architectural design, such as architects and architecture students, complemented by a broader group of volunteers from outside this field. Most of the participants were students from TU Delft, with sometimes more engineering backgrounds rather that architectural, reflecting the network most accessible during this phase of the research. (Figure 86)

The collected data were analyzed to identify recurring patterns, preferences, and opportunities, which could lead the optimization of CoRncrete's aesthetic direction and its suitability for architectural use.

	Participant type	Sample order
Participant 1	Mechanical engineering BSc student	1-2-3
Participant 2	Architecture BSc	1-3-2
Participant 3	Mechanical engineering MSc student	3-1-2
Participant 4	Building engineer PhD	2-3-1
Participant 5	Architect	3-2-1
Participant 6	Technical medicine MSc student	1-3-2
Participant 7	Mechanical engineering MSc	2-1-3
Participant 8	Architecture MSc student	1-2-3
Participant 9	Industrial Design MSc	2-1-3

Figure 86 - Overview of different types of participants and the sample order they were shown.

Characterization
Experiential

Performative
The performative level explains the engagement between people and materials. It shows the ways in which materials invite certain actions or behaviors, shaping how we handle and interact with them. For instance, a surface may encourage caressing, tapping, or bending, making us want to explore its possibilities. (Karana, 2009).

-Results
The results are shown using bar charts. For every sample, the performed action, together with the amount of times the action occurred, are shown.

For the plain sample, Picking, Holding, Grabbing, and Compressing were performed by most participants (≥8). Picking, Holding, and Grabbing were the three actions performed by all 9 participants. In contrast, Smelling and Pressing were performed by only 1 participants. Overall, ten different actions were performed with the Plain sample. (Figure 88)

For the marbled sample, Picking, Holding, Grabbing, and Compressing were again performed by most participants (≥8). Picking, Holding, and Grabbing were performed by all 9 participants. Actions such as Smelling and Weighting were performed by fewer participants, while Knocking was only reported once. In total, eleven different actions were performed with the Marbled sample. (Figure 89)

For the pigmented sample, Picking, Holding, and Grabbing were again the most common actions, performed by all 9 participants. Compressing was less frequently performed compared to the other two samples. Most action had similar frequencies, but one participant spinned the sample (Figure 87). Nine different actions were performed with the Pigmented sample. (Figure 89)

-Conclusion
Across all three samples, participants consistently relied on core tactile actions such as Picking, Holding, and Grabbing, indicating that these interactions form the foundation of material engagement regardless of surface variation.

Subtle differences, however, point to varying levels of curiosity. The plain sample prompted a stable yet limited range of actions, while the marbled sample elicited the broadest variety (11 actions), suggesting that its patterned qualities encouraged additional exploration such as Knocking and Weighting. The pigmented sample showed slightly fewer actions overall but stood out with a unique behavior (Spinning), reflecting a more experimental response.

Overall, while the three samples triggered largely similar performative patterns, the marbled and pigmented variants appear to foster slightly greater curiosity, occasionally leading participants beyond predictable tactile routines.

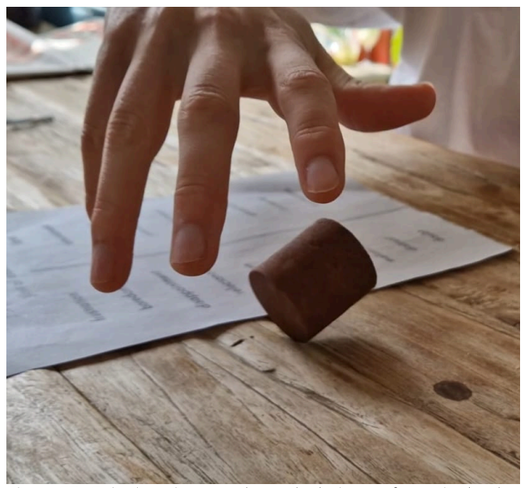


Figure 87 - Spinning pigmented sample during performative level.

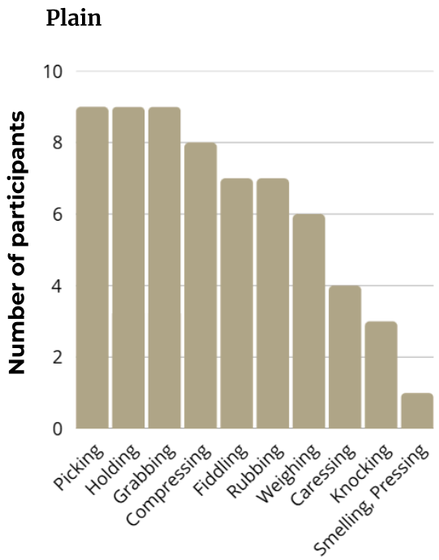


Figure 88 - Performative experience graphs plain sample.

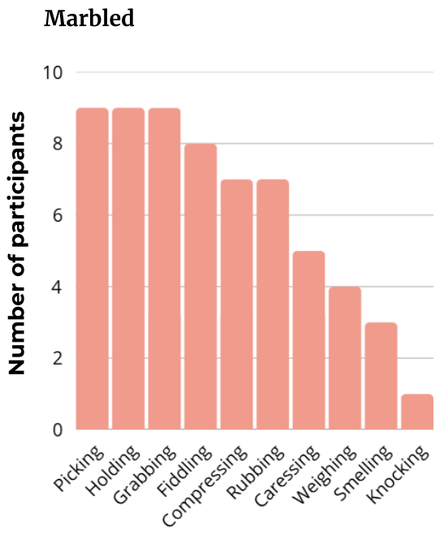


Figure 89 - Performative experience graphs marbled sample.

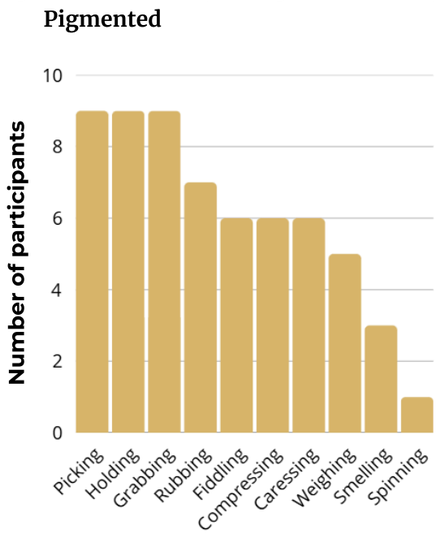


Figure 90 - Performative experience graphs pigmented sample.

Characterization
Experiential

Sensorial
The sensorial level refers to our encounter with materials through the senses through touch mostly. At this stage, we respond directly to the surface qualities and physical sensations a material evokes. For example, we might perceive a texture as smooth, rough or hard. These initial impressions shape how pleasant or unpleasant the material feels to interact with, making the sensorial level the foundation of our material experience. (Karana, 2009).

-Results
The results are mapped out per sample. For each sensory topic, the average between all participants is shown in a graph (dots connected by line) together with the range in which answers were given (transparent dots). In Figure 94, you see the average of the 3 different samples in comparison.

The results for the plain sample show the highest standard deviations (SD) for Hard/Soft (SD = 2.44), Fibred/Not fibred (SD = 2) and Regular texture/Irregular texture (SD = 1.78). The results show the lowest SD's for Tough/Ductile (SD = 0.89), Opaque/Transparent (SD = 0.89) and Not reflective/Reflective (SD = 1.22). (Figure 91)

The results for the marbled sample show the highest standard deviations (SD) for Regular texture/Irregular texture (SD = 2.22), Fibred/Not fibred (SD = 2.22) and Matte/Glossy (SD = 2.11). The results show the lowest SD's for Not elastic/Elastic (SD = 0), Not reflective/Reflective (SD = 0.56) and Opaque/Transparent (SD = 0.89). (Figure 92)

The results for the pigmented sample show the highest standard deviations (SD) for Tough/Ductile (SD = 2.56), Fibred/Not fibred (SD = 2.56) and the third spot is shared with Hard/Soft, Smooth/Rough and Strong/Weak (SD = 2.44). The results show the lowest SD's for Not elastic/Elastic (SD = 0), Opaque/Transparent (SD = 0) and Matte/Glossy (SD = 0.56). (Figure 93)

-Conclusion
Taken together, the results suggest that while certain material qualities (elasticity, transparency) were perceived uniformly across participants, others (texture, fiber presence, toughness) were highly open to interpretation. This might indicates that said ambiguous sensory attributions, are unclear in relation to the samples, that terms used in the questionnaire were unclear or multi-interpretative, or that circumstances were different per participant.

Despite these variations, the averages across all three samples align closely, indicating that participants attributed broadly similar sensory characteristics to each material. This suggests that while individual judgments varied in intensity, the overall sensory attribution is largely consistent across the samples. (Figure X)

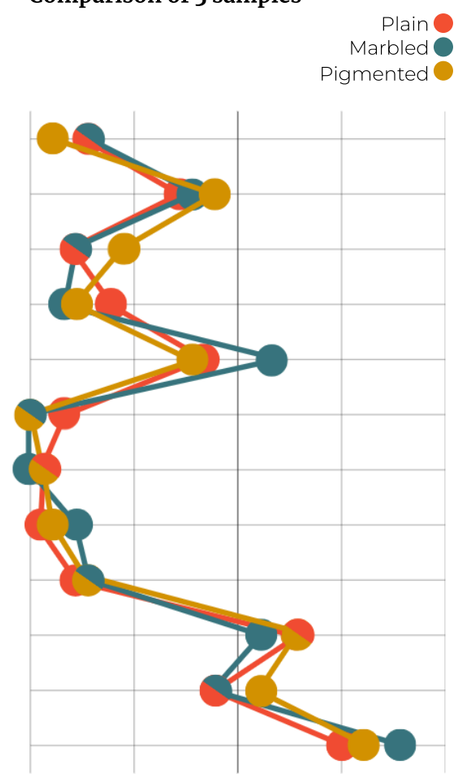


Figure 94 - Sensory experience comparison graph.

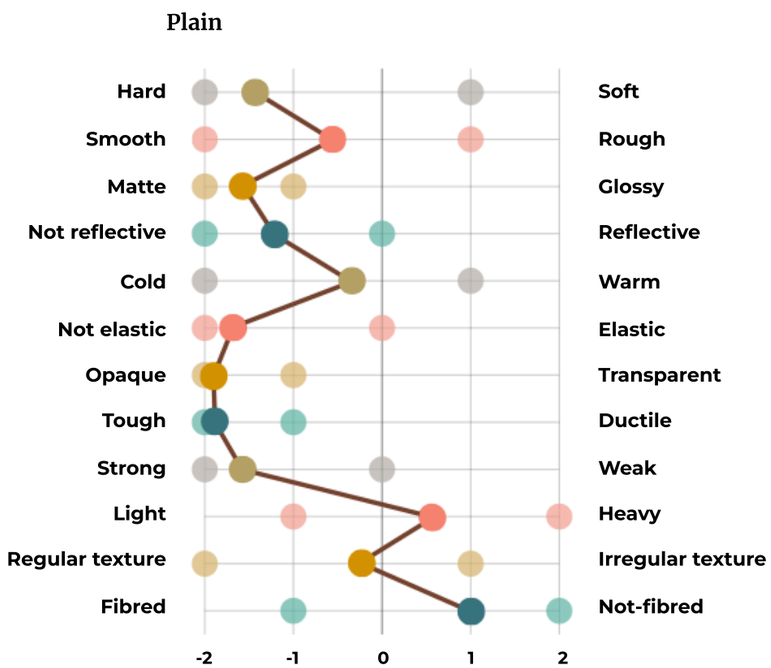


Figure 91 - Sensory experience graphs plain sample.

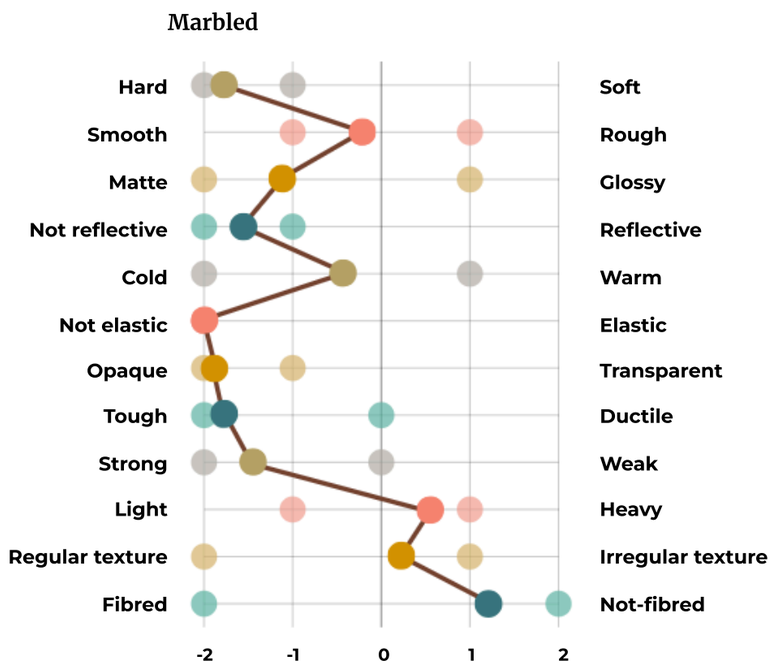


Figure 92 - Sensory experience graphs marbled sample.

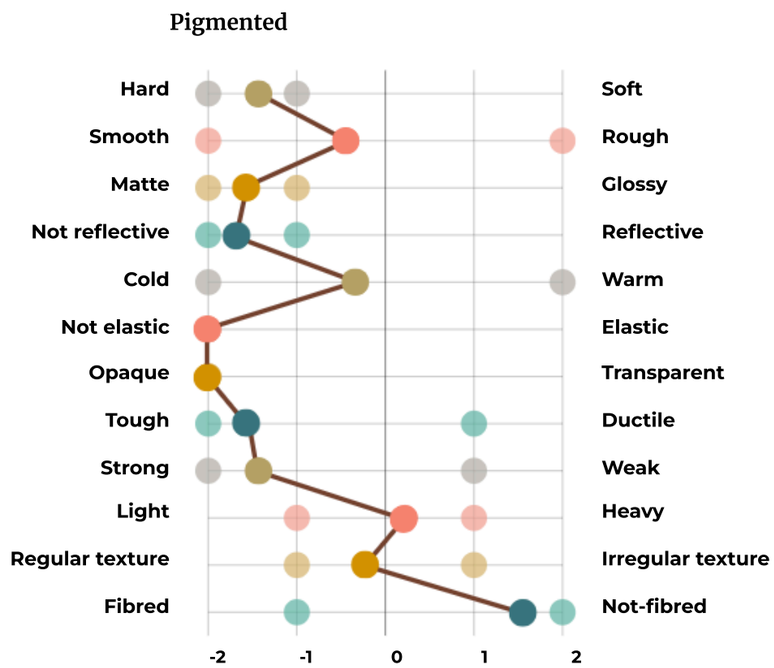


Figure 93 - Sensory experience graphs pigmented sample.

Characterization
Experiential

Interpretive
The interpretive level goes beyond immediate perception and focuses on the meanings we assign to materials. A product might be labeled as modern, traditional, luxurious, or cheap depending on someone's perception. This level highlights how context, prior knowledge and opinion influence the way we evaluate and categorize materials. (Karana, 2009).

-Results
The results are shown using bar charts. Per sample, the attributes mentioned, together with the amount of times they have been mentioned, are shown.

For the plain sample, 31 attributes were given, consisting of 17 different ones. The attributes Sober, Cold and Sand-ish all contributed 12.90% to the total amount of attributes. The attributes Concrete, Old, Manufactured all contributed 9.68% to the total amount of attributes. One interesting attribute that was only mentioned ones was Used, which correlated to the gray stains on the sample. (Figure 95)

For the marbled sample, 34 attributes were given, consisting of 23 different ones. The attributes Playful and Natural both contributed 11.76% to the total amount of attributes. The attribute Manufactured contributed 8.82% to the total amount of attributes. This sample got a lot of single original attributes like Cookie, Dog food and Cork. (Figure 97)

For the pigmented sample, 30 attributes were given, consisting of 17 different ones. The attribute Masonry brick contributed 16.67% to the total amount of attributes. The attribute Warm contributed 13.33% to the total amount of attributes. The attributes Tough and Reliable both contributed 10% to the total amount of attributes. A few interesting attributes that were given once were Nostalgia and Chalk. (Figure 98)

Both Masculine and Feminine were mention once.

There was a clear distinction between answers from architects or architecture students and engineers. Relatively, the engineers tended to give answers that were more bound to the reference sheet that was given. The architects or architecture students tended to give more creative interpretations like Cork an Chalk.

-Conclusion
When comparing the three samples, clear differences emerge in how participants interpreted their qualities. The plain sample evoked relatively conventional and restrained associations, often tied to its sober and manufactured appearance. By contrast, the marbled sample triggered the widest variety of interpretations, including playful and unexpected associations such as Cookie or Dog food, suggesting that its patterning stimulated more imaginative responses. The pigmented sample sat between these two extremes: while many participants described it in functional and structural terms (Masonry brick, Tough, Reliable), some also linked it to more symbolic attributions such as Nostalgia.

Taken together, the results show that while all three materials were anchored in familiar, material-related descriptors, the marbled and pigmented samples invited more divergent and curiosity-driven attributions compared to the plain sample. Furthermore, disciplinary background shaped interpretive tendencies: engineers leaned toward reference-based descriptions, whereas architects and architecture students offered more creative associations. This highlights that both material qualities and user perspective play a decisive role in the breadth of interpretive engagement.

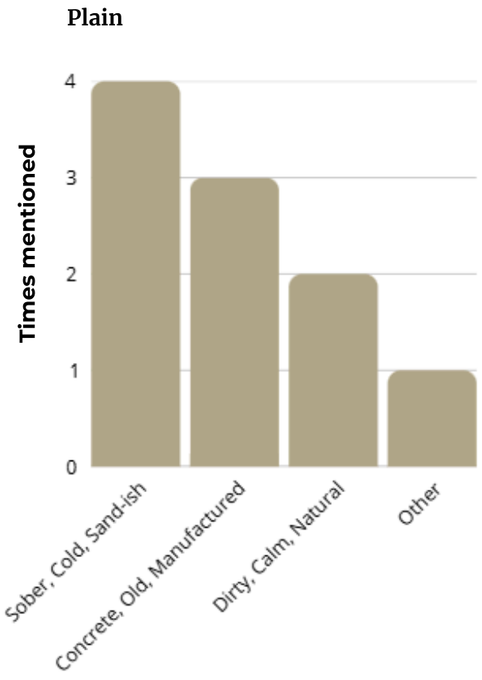


Figure 95 - Interpretive experience graphs plain sample.

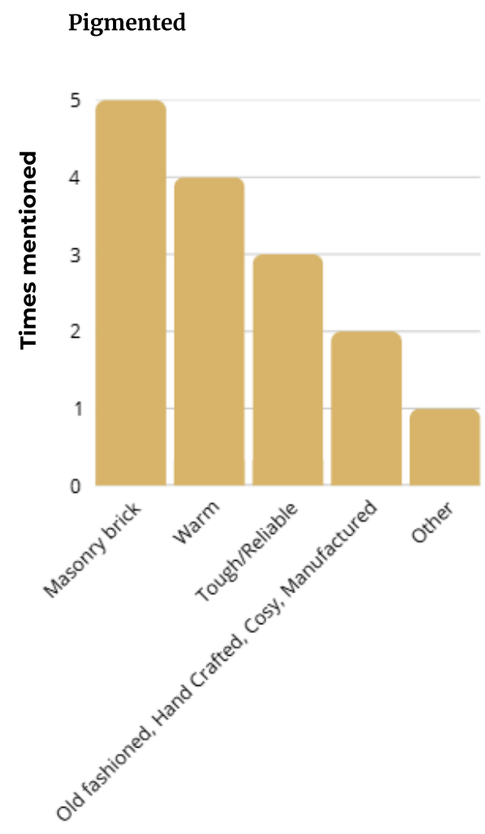


Figure 96 - Interpretive experience graphs pigmented sample.

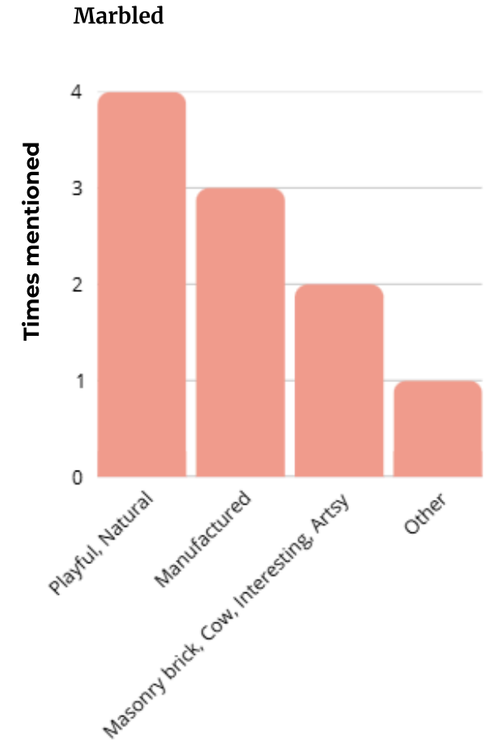


Figure 97 - Interpretive experience graphs marbled sample.

Characterization
Experiential

Affective
The affective level emphasizes the emotional responses materials can evoke. Materials may spark fascination, surprise, comfort, or even disappointment depending on their qualities and how they are presented. At this stage, the emphasis lies on how materials resonate with us emotionally, showing the possible effects this material has on the user in context. (Karana, 2009).

-Results
Per sample, the emotions mentioned are mapped out in a graph. The emotions are mapped based on if they are positive or negative emotions and based on their intensity. Emotions that were mentioned more often were clustered and shown using a colored shape. This way, the spread of the emotions over the graph stays visible.

For the plain sample, 3 out of 9 participants felt Calm and Indifference. 2 out of 9 participants felt Comfort and Amusement. A few negative emotions were mention apart from the indifference that also leans to negative feelings. Mostly positive feelings were mentioned with low to moderate intensities. (Figure 98)

For the marbled sample, 7 out of 9 participants felt Curiosity, 4 out of 9 felt Surprise, 3 out of 9 felt Amusement and 2 out of 9 felt Calm. Almost no negative emotions were mention apart from the clustered feeling leaning over to the negative side. The feelings mentioned had low to moderate intensities. (Figure 99)

For the pigmented sample, 5 out of 9 participants felt Comfort, 3 out of 9 felt Calm and 2 out of 9 felt Trust and Indifference. A few negative emotions were mention next to the indifference that also leans to negative feelings. Mostly positive feelings were mentioned with moderate intensities. (Figure 100)

There was again a distinction between architects or architecture students and engineers. Although the engineers all varied in responses, it was noticeable that the architects or architecture students were able to distance themselves a little more from the sample they were given and see the given sample in context. It is believed that this lead to less intense emotions and/or less negative emotions mentioned by tem

-Conclusion
Across the three samples, participants primarily reported positive emotions of low to moderate intensity, though the type of emotions varied by material. The plain sample evoked calmness and indifference, reflecting a more neutral or subdued affective response. The marbled sample stood out by eliciting strong curiosity and surprise in most participants, suggesting that its patterned appearance stimulated more active emotional engagement than the other materials. The pigmented sample evoked feelings of comfort, calm, and trust, positioning it between the plain and marbled samples. It balances reassurance with slight emotional variation.

Overall, the findings show that all three samples were viewed in a positive way. The marbled sample, however, stood out by evoking more exploratory emotions, while the plain and pigmented samples were linked to calmer and more stable feelings. This suggests that even small variations in material qualities can influence whether people respond with neutrality, reassurance, or curiosity.

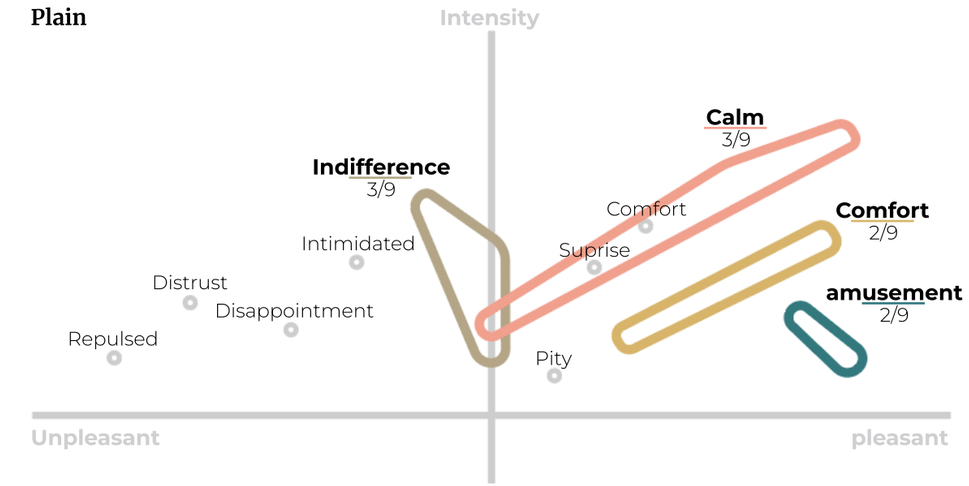


Figure 98 - Affective experience graphs plain sample.

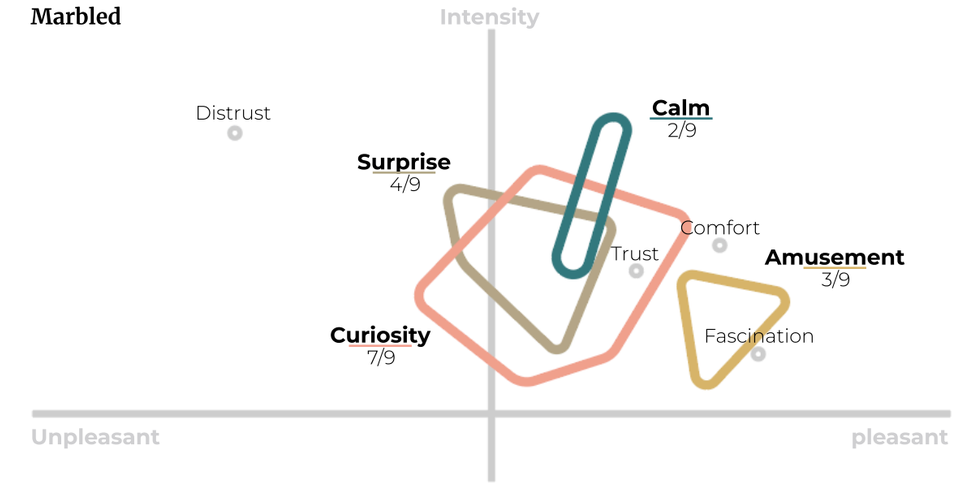


Figure 99 - Affective experience graphs marbled sample.

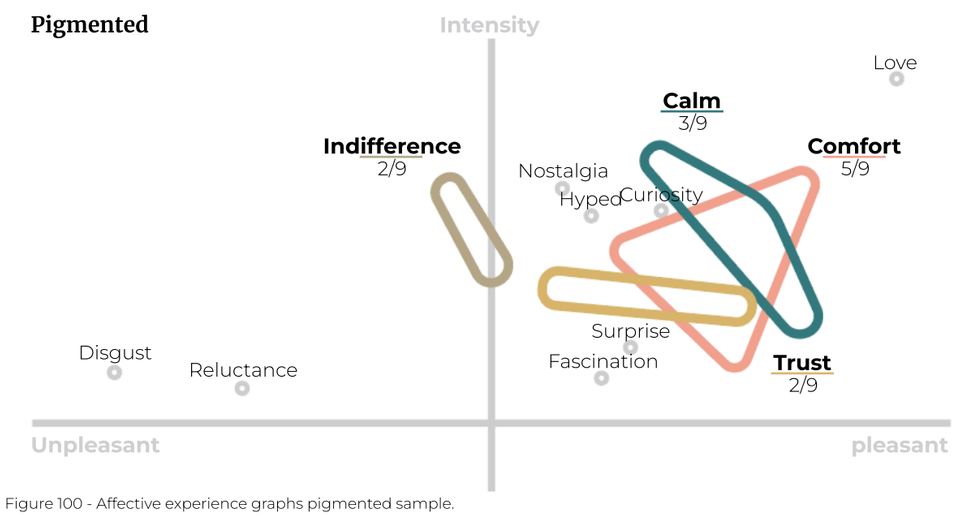


Figure 100 - Affective experience graphs pigmented sample.

Characterization
Experiential

Conclusion
Across all four levels of material experience, sensorial, performative, interpretive, and affective, a pattern emerges: while participants consistently engaged in similar core behaviors and perceptions across the samples, the marbled and pigmented materials tended to stimulate more diverse, curiosity-driven, and imaginative responses compared to the plain sample. This indicates that subtle differences in visual and surface qualities can broaden the scope of interaction, interpretation, and emotion, even when fundamental tactile and sensory experiences remain stable.

With these results, it is assumed that all 3 samples are desirable options for architectural application, all 3 in their own way.

-Plain sample
This sample evoked the most stable and conventional responses, with lower variability in interpretation and emotion. Participants engaged mainly in core tactile actions and described the sample in grounded, material-related terms. Emotionally, it leaned toward neutrality and calmness.

This sample could function well in an architectural application where it has to keep in the background. This way, the plain sample can form a neutral and calm contrast to any other focal points used in the room. The architects that have participated in this research, confirmed this need by mentioning the importance of “boring” materials in the decoration of a building.

-Marbled sample
This sample stood out as the most curiosity-inducing and exploratory sample. It generated the widest variety of performative actions, the highest diversity of interpretive attributions (including playful and unexpected ones), and the affective responses like Curiosity and Surprise. It demonstrates how patterned variation can expand engagement across all levels. Some participants mentioned that the sample might be overwhelming when used over a larger surface like a wall.

It is believed this sample could function best as a focal point on its own, drawing attention and being in the foreground. Other application where curiosity and amusement are the main objective, can be considered for this sample.

-Pigmented sample
This sample balances between stability and exploration. While it shared the core tactile and sensory consistencies with the plain sample, it also triggered some unique actions (Spinning) and interpretive or affective attributions tied to symbolism (Nostalgia). Emotionally, it leaned toward reassurance and comfort but still allowed space for more imaginative responses.

This sample could function well as a inviting and interesting surface, that still functions as a background. Instead of a paint on the wall, this sample would create character and depth to a room without taken the foreground.

Discussion
-Participant pool in user tests
The user study was carried out with people who had a fairly similar background and were close in age. Because of this, the results cannot be seen as fully representative of the wider population or the range of possible viewpoints. Only two participants had a professional background in architecture, which also reduced the amount of expert feedback in the study. A more mixed group of participants would have made the findings stronger and easier to generalize.

Summary
In this chapter, a study was conducted to examine the user experience and perception of CoRncrete, rather than how it performs in tests. To explore this, nine participants, mostly students with backgrounds in design, architecture, or engineering, joined short sessions using the Material Driven Design (MDD) Experiential Characterization toolkit. They examined three variants: a plain sample with eggshell powder, a pigmented sample made with Spanish red oxide. and a marbled sample with the same oxide. During the sessions, the participants ranked the sample’s sensory qualities, discussed their associations and emotions connected to the samples, and were observed while handling the pieces. They were also asked to compare recipe 0, without eggshells, to the eggshell-based mix, and gave feedback on other color options.

-Results
The results showed that people interacted with all three samples in broadly the same way, but the surface finish made a difference to how much curiosity each one inspired. The marbled piece invited the widest range of actions, words, and emotions, often linked to surprise or playfulness. The pigmented sample sat somewhere in the middle, offering a sense of comfort while still sparking a few symbolic or nostalgic links. The plain sample felt calm and familiar, which made it seem well suited as a quiet background material.

-Conclusion
Taken together, the findings suggest that all three options can work in architectural settings, though in different roles. The plain surface lends itself to calm interiors, the marbled one could become a focal point, and the pigmented version adds warmth without demanding too much attention.

Application

Application
Design

In this chapter, the application of CoRncrete in the architectural sector is explained by answering the design goal set at the start of this project:

"Optimizing CoRncrete into an architectural pre-cast concrete alternative by improving moisture resistance and aesthetics, while maintaining its sustainable advantage"

Since the recipe no longer contains corn, the name has been changed from CoRncrete to Agristone.

Context
Argistone is based on the concept of a pre-cast concrete block replacement for load bearing construction in low-rise buildings. It's intent is to be used for the inner leaf of cavity walls as well as in partition walls. The blocks can be used both with or without plaster, assuming it is fire resistant, creating more options for Agristone's use for its aesthetics.

Ingredients
The recipe of the Agristone blocks is based on the best performance in the technical characterisation chapter. The sample containing 12.5% sand replacement with eggshell powder, had the highest measured UCS and no distinguishable water resistance in comparison to the other samples. The percentages relative to weight of the different ingredients of Agristone are shown in Figure 101.

Manufacture method
The manufacture method for Agristone blocks is based on the "wet in mold" approach, eliminating 3 steps of the original manufacture method of CoRncrete. This includes a step where energy is needed for the oven. The reduction in steps has the most effect on the labor intensity of the manufacture method. Without having to granulate the mixture, less manual labor is needed.

The new manufacture method exists of the following steps which are also shown in Figure 102:

1 - Mixing:
The sand and potato starch are mixed thoroughly using a whisk.

2 - Hydration:
Water is added to the dry mix and stirred again to ensure even distribution.

3 - Casting:
The wet mixture is poured into a silicone mold, covered with aluminum foil.

4 - Baking:
The wet mixture is baked in a conventional lab oven at 120°C with 50% airflow and fan for 2 hours.

5 - Pressing:
The baked mixture is broken up into pieces and then pressed at 4 tonnes in a cylindric mold.



Figure 101 - Ingredient proportions based on weight of 12.5% eggshell powder sand replacement.

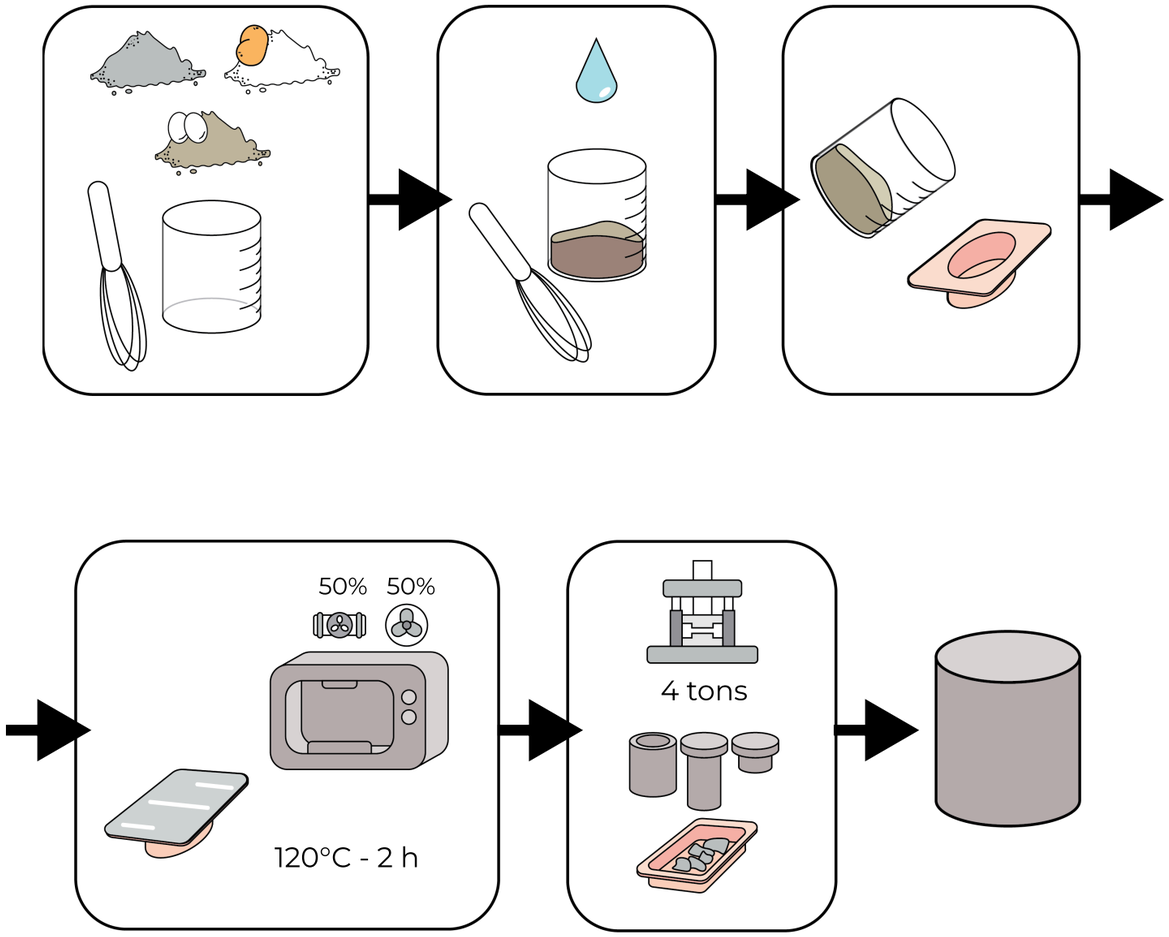


Figure 102 - New manufacturing process, mixture wet in mold.

Application
Design

Shape, dimensions and properties
The block is designed in a familiar shape to the architecture sector, with current dimensions of 300 mm × 100 mm × 200 mm (Figure 103), aligning with conventional precast concrete blocks for ease of integration in construction practises. It has an estimated density of approximately 1,800 kg/m³ based on the samples in the research. The ultimate compressive strength is estimated at 14 MPa, enabling its use as a loadbearing element in low-rise structures following Irish standards for concrete masonry (ACEI Structures Committee, 2022). It also falls within the lightweight structural concrete compressive strength range (11.3 - 28 MPa) (Ansys, 2021). Furthermore, the block is assumed to possess adequate water resistance to withstand non-persistent but high loads of water.

Installation
Argistone blocks can be installed using traditional masonry techniques like mortar. However, when combined with innovative masonry solutions, that make recovery of old blocks easier, the blocks can be recovered at the end of a building's service life and reused in new projects. This is especially important since the interviews in this report concluded that pre-cast concrete options are currently chosen for the option to later reuse the parts. the option for reusability significantly extends the service life of the material, increases its sustainable potential, and increases its overall desirability within the construction sector. In this way, Argistone not only reduces impact at the production stage but also contributes to circular construction practices at the end of life.



Figure 103 - Agristone dimensions, aligning with conventional precast concrete blocks.

Product	Thermal resistance assumption	Source
Agristone	Rc = 0.07 m²K/W	(Stowell Concrete | 100mm Dense Concrete Block 7.3N/mm2, n.d.)
Wood fiber insulation	λ = 0.040 W/m·K	(GreenSPeC: Wood Fibre Insulation: Introduction, n.d.)
Celit board	Rc = 0.44 m²K/W	(EcoBati | EcoBati | Product CELIT 4D 22MM 595 X 2500, n.d.)
Wooden cladding	Thin and negligible, ignored here	

Figure 104 - Assumptions on thermal resistance of different elements in wall assembly.

Example situation
In its final application, Agristone can serve as the load-bearing inner leaf in a multilayer wall assembly. The example below illustrates a possible scenario, which has also been translated into a scale model (Figure 107, 108 & 109). The wall assembly runs from inside to outside and consists of the following layers:

- Agristone load-bearing wall (10 cm thick) – functions as the inner leaf and carries the structural load. It is assumed that the fire resistance is sufficient for low-rise applications.
- Wood fiber insulation – the thermal layer; thickness depends on the desired energy performance.
- Celit wood fiber board (22 mm thick) – a weather-resistant, compressive, wood fiber panel that protects the insulation and contributes to wind and air tightness.
- Wooden cladding – the visible outer finish, providing aesthetic quality.

-Calculations
The following calculations on wall thickness in relation to the wall's thermal resistance, are based on the assumptions in Figure 104. The main contributor to the wall thickness is the insulation since this part has to compensate for potential shortcomings in thermal resistance of the other materials. Since there is no data yet for thermal resistance of Agristone, it is assumed that it has a similar thermal resistance as concrete. Concrete is know for its relative low thermal resistance.

These are the thermal resistance (Rc) targets mentioned in the list of Requirements & wishes:

- Rc = 4.7 m²K/W (Isodirect B.V., 2023)
- Rc = 6.7 m²K/W (Passive House Institute Dr. Wolfgang Feist, n.d.-b).

To calculate the needed amount of Rc for the insulation, the Agristone and Celit Rc have to be subtracted from the target value.

$$4.70(m^2K/W) - (0.07(m^2K/W) + 0.44(m^2K/W)) \approx 4.19m^2K/W$$
$$6.70(m^2K/W) - (0.07(m^2K/W) + 0.44(m^2K/W)) \approx 6.19m^2K/W$$

To calculate the thickness of the insulation layer, the calculated Rc value for insulation has to be multiplied by its λ-value.

Application
Design

Wall in-out 312 mm

- Agristone 100 mm
- Insulation 170 mm
- Wood fiber panel 22 mm
- Cladding 20 mm

$4.19(m^2K/W) * 0.040(W/mK) = 0.168m \approx 17cm$
$6.19(m^2K/W) * 0.040(W/mK) = 0.248m \approx 25cm$

With these two thicknesses for insulation, the total wall thickness (inner to outer) will be 31.2 cm (Rc = 4.7 m²K/W) and 39.2 cm (Rc = 6.7 m²K/W). The example situation for both thicknesses are shown in Figure 105 and 106.

-Conclusion

This example demonstrates how Agristone can function effectively as a load-bearing inner wall in an energy-efficient assembly. The wood fiber insulation determines the final performance and can be flexibly dimensioned depending on the ambition (standard or Passive). The Celit board adds weather resistance, while the wooden cladding ensures aesthetic appeal. Most Dutch houses have wall thicknesses no greater than 40 cm. This calculation shows that both standard Dutch norms (BENG) and Passive House standards are feasible within this typical wall width. Additionally, the insulation value used for Agristone is based on a standard precast concrete insulation number, which is relatively low compared to many other building materials. This makes the calculation conservative, meaning the actual thermal performance could be slightly better than estimated.

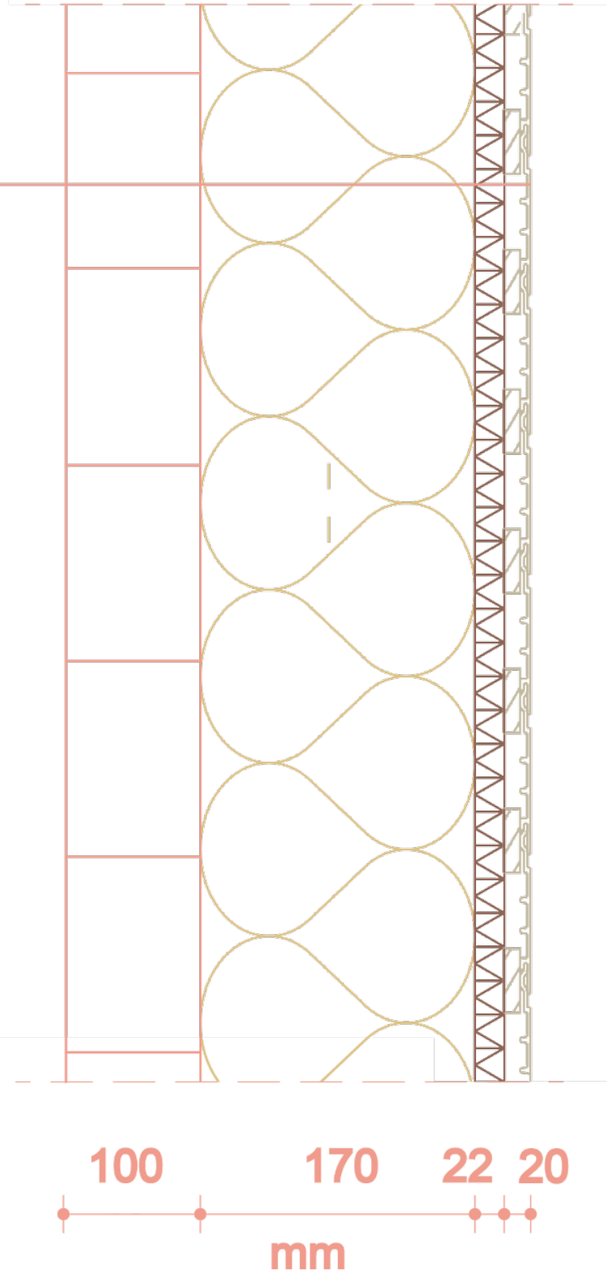


Figure 105 - Example situation of wall assembly cross section (Rc = 4.7 m²K/W).

Wall in-out 392 mm

- Agristone 100 mm
- Insulation 250 mm
- Wood fiber panel 22 mm
- Cladding 20 mm

Discussion

-Fire safety of Agristone

At this stage, many important details regarding fire safety have not yet been addressed. It is possible that a dedicated fire-protective layer will be required to meet regulatory standards. The addition of such a layer could prevent the brick wall from being left fully exposed, which would affect both the aesthetic appearance and the total wall thickness.

-Missing details in cross-section

The current design only shows the basic layering of Agristone, insulation, Celit board, and cladding without detailed consideration of how the materials are attached or integrated within the wall. In practice, fasteners, brackets, and interface layers between different materials could be required to ensure structural stability, airtightness, and long-term durability. These additions could increase the total thickness of the wall. Detailed structural and construction planning is therefore necessary to confirm the feasibility of the proposed assembly.

-Absence of a physical final design

The project did not result in a full-scale prototype, mainly due to limits in time and resources. This means that the assessment of Agristone as a precast block stayed partly theoretical. The smaller test samples still gave useful information, but without a finished block it was not possible to properly evaluate factors like manufacturability, handling, and real-world performance.

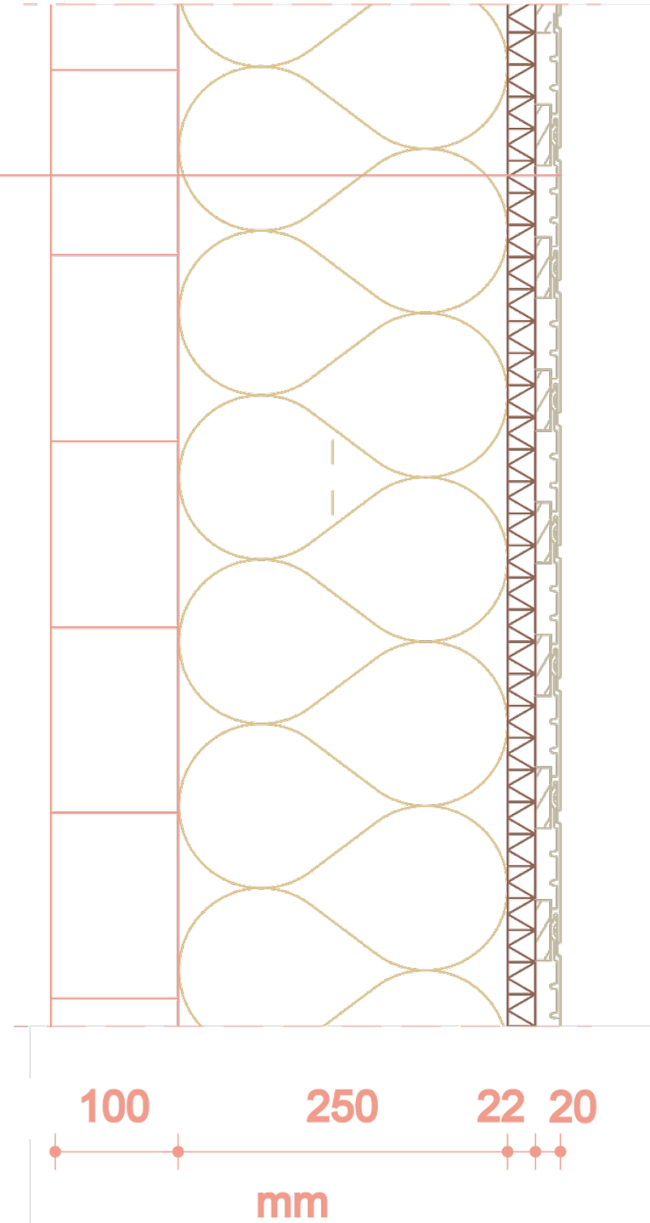


Figure 106 - Example situation of wall assembly cross section (Rc = 6.7 m²K/W).



Figure 107 - Showcase scale model Agristone blocks 1:10 scale.

Application
Design



Figure 108 - Showcase scale model cross section (Rc = 6.7 m²K/W) 1:10 scale.



Figure 109 - Showcase scale model Agristone block wall 1:10 scale.

Application
Desirability

In material and product design, it is not enough to focus only on technical performance or cost. To make it more relevant in architectural settings and to widen its appeal, a product extension has been added.

With this extension, Argistone grows from being only a sustainable alternative to concrete into a broader material system that combines performance, visual richness, and identity.

Line extension

This product extension gives architects and designers more freedom by offering several natural color options alongside the plain, concrete-like base. The pigments, made from oxides (Figure 110) include Burnt Umber, Spanish Red Earth, Dutch Roof Tile Red, Yellow Ochre, and Bohemian Green (Figure 112 & 113). They can be used separately to add variation and depth to walls, or mixed in the marbled version, where the colors blend into unique patterns (Figure 111). Because of its striking appearance, the marbled version is mainly intended for projects that call for a strong visual impact or an expressive architectural statement.

In this way, the material brings together functionality, sustainability, and visual expression. It is not only a sustainable building material, but also a versatile and visually engaging option compared to standard concrete blocks. This widens Argistone's appeal: it speaks both to clients focused on sustainability and to architects who value design freedom and aesthetics.

The colored blocks also have practical benefits. Their finish removes the need for extra interior treatments, which reduces construction steps and at the same time creates an authentic look with more character. The pigments are fully sustainable, coming from natural earth sources or from secondary streams such as rooftop tile waste, and they are processed with wind energy in a traditional Dutch windmill. This strengthens Argistone's ecological story while linking it to local craftsmanship and heritage.



Figure 110 - Spanish red oxide powder.



Figure 111 - Marbled sample burnt umber and roof tile red.



Figure 112 - Oxides samples (Burnt umber, Spanish red , roof tile red, ochre yellow, green bohemian earth).



Figure 113 - Oxides samples in sample box for architects

Application
Viability

In order to evaluate whether the proposed material can realistically be adopted in the building industry, it is essential to assess its economic and environmental viability. This chapter therefore presents a sustainability analyses and cost calculations, comparing Agristone with conventional concrete blocks and alternative building materials.

Sustainability

To assess Agristones sustainable advantage against regular pre-cast concrete blocks, a calculation is done. The comparison focuses on embodied energy (MJ) and CO_2 emissions (kg CO_2) per block. These indicators are commonly used to assess sustainability because:

- Embodied energy measures the total energy required to produce a material, reflecting the resource intensity of its production. If fossil fuels are used to generate this energy, more CO_2 is emitted, contributing to climate change. However, energy consumption could be partially mitigated if renewable energy is used.
- CO_2 emissions provide a direct estimate of the contribution of the material production to greenhouse gas emissions, which are strongly linked to global warming.

Only the energy and CO_2 related to material production and heating are considered. Transport, construction, and end-of-life phases are excluded.

Data quality levels are used to simulate the level of uncertainty in the assumptions done during this calculation. The use of these quality levels are roughly based on ILCD frameworks and specifically on their use by ROYER en TU Delft (2025). The used ranges in percentages are shown in Figure 114.

All calculations are based per block of Agristone or structural lightweight concrete. With the dimensions and density of the blocks, and the percentages per weight, the weight per ingredient was calculated (Figure 115 & 116). These weights will later be used to calculate the impact per block.

-Raw material assumption

For the regular pre-cast concrete, an energy use of 0.819 MJ/kg and an emission of 0.122 kg CO2 eq/kg was assumed, based on averages in structural lightweight concrete (Ansys, 2021). For Agristone, these values are a combination of those of the potato starch, sand and eggshell powder relative to their weight in the block. The contribution of water will be ignored due to negligible contributions. Potato starch (non-food grade) can have an energy use of 0.252 MJ/kg (Huatai, 2024). The emissions of potato starch in the food grade industry is 1.45 kg CO2 eq/kg (CarbonCloud, n.d.), but a non-food grade retailer states that their product has 67% lower emissions compared to food grade retailers (Duynie | Life Cycle Assessment Potato Starch, n.d.), meaning that a emission of 0.48 kg CO2 eq/kg can be assumed for non-food grade potato starch. For the sand used in the Agristone, an average energy use of 0.081 MJ/kg and an emission of 0.0099 kg CO2 eq/kg is assumed (Ansys, 2021). Averages from limestone production were used as indication for the possible energy use and emission of eggshell powder production due to the similarities is chemical composition (CaCO3). Therefore, an average energy use of 0.295 MJ/kg and an emission of 0.0155 kg CO2 eq/kg can be assumed (Ansys, 2021).

-Process Energy

For the energy use calculations of manufacturing process, the specs of a lab grade oven are used. The power consumption of such oven is assumed to be 1000 W (Tradeindia, n.d.). The oven is used at full power until a temperature of 120 degrees is achieved (E-heatup). After that the over will use less power to stay at

Data quality level	Indicative criteria	Uncertainty to apply (%)
Very good	Directly measured data, recent, specific to the case study	10
Good	Specific but estimated data from reliable sources or technical reports	20
Medium	Generic data from databases, not fully representative	30
Poor	Approximate or outdated data, not well adapted to the case	50
Very poor	Data based on extrapolations, uncertain assumptions, or from very different geographic contexts	70

Figure 114 - Data quality level ranges by ROYER en TU Delft (2025).

Material	Volume (m3)	Density (kg/m3)	Weight (kg)
Agristone	0.006	1800	10.8
Lightweight structural concrete	0.006	2000	12

Figure 115 - Volume, density and weight of Agristone and lightweight structural concrete.

Ingredients Agristone	Percentage (%)	Weight per block (kg)
Sand	62.05	6.70
Potato starch	14.08	1.52
Demi water	15.01	1.62
Eggshells	8.86	0.96

Figure 116 - Calculated weigth per ingredient in an Agristone block.

Application
Viability

that temperature for 2 hours (E-steadystate). It is assumed that the oven will use about 25% of its original power for the steady state time. Energy used [J] is calculated by multiplying power [W] with time [s]. A preheating time of 15 minutes is used. The CO2 eq emissions of the material itself when heated are negligible since the CaCO3 of the eggshells are not yet decomposing into Ca(OH)2 and CO2.

The data quality levels of raw material assumptions and the process energy, together with an explanation, are shown in Figure 119.

-Total Values per Block

Figure 117 and 118 show for both materials the total embodied energy and the total emission that an Agristone block has a lower impact than the concrete block. Even when comparing the worst case scenario of Agristone with the best case scenario of the structural lightweight concrete, Agristone still performs slightly better.

It is also noticeble that the ultimate difference between worst case, reference, and best case are lower for Agristone than for concrete. This might partly be due to the higher impact of which a percentage is taken.

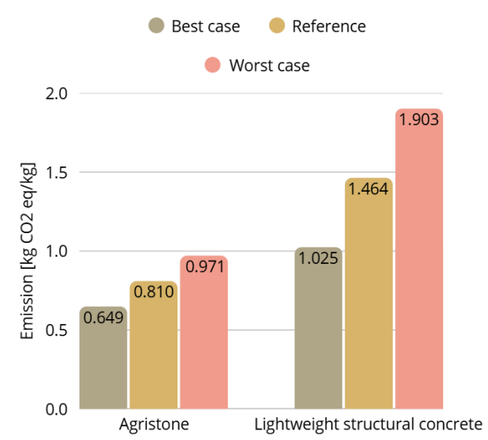


Figure 117 - Total emissions of Agristone and lightweight structural concrete together with best and worst case scenario.

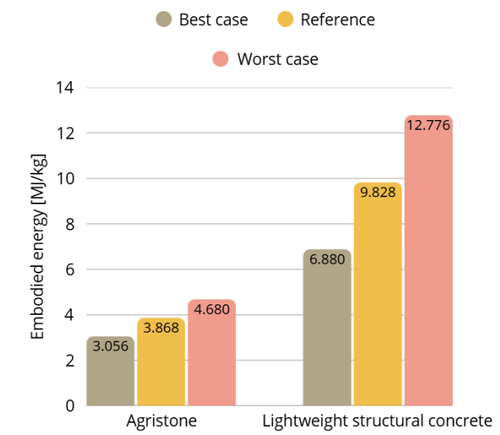


Figure 118 - Total embodied energy of Agristone and lightweight structural concrete together with best and worst case scenario.

-Ingredient contribution

Figure 120 and 121 show for both the total embodied energy and the total emission the contribution of the different ingredients to the impact of Agristone. Noticeble is that the impact of the ingredient differs for embodied energy or emissions. In embodied energy, send has the highest impact, followed by potato starch and after eggshell powder. However, the worst case scenario of eggshell powder rises above the reference of potato starch.

The emissions of potato starch rise high above the other two ingredients. Second is sand and eggshel powder is almost negligible.

-Conclusion

Within the material manufacturing process (Cradle-to-gate) the Agristone block is assumed to consume less energy and emit less CO_2 than a concrete block, both with dimensions of 300mm x 100mm x 200mm. If the original manufacture method was used, the energy used would have increased with 1.35 MJ, making Agristone still the prefered choice over concrete. When comparing Agristone's worst case scenarios with concrete's best case scenarios, there is only a small difference left. In this comparison it is more difficult to

Assumption	Uncertainty (%)	Justification
Potato starch embodied energy of 0.252 MJ/kg	15	Based on shared date from potato starch company
Potato starch emission of 0.48 kg CO2 eq/kg	20	Based on live calculations with a source based factor
Sand embodied energy of 0.081 MJ/kg	10	Based on well know material database
Sand emission of 0.0099 kg CO2 eq/kg	10	Based on well know material database
Eggshell powder embodied energy of 0.295 MJ/kg	70	Based on substituted material data with similar material composition, but different origin
Eggshell powder emission of 0.0155 kg CO2 eq/kg	70	Based on substituted material data with similar material composition, but different origin
Lightweight structural concrete embodied energy of 0.819 MJ/kg	30	Based on well know material database, but not the exact material type for the application
Lightweight structural concrete emission of 0.122 kg CO2 eq/kg	30	Based on well know material database, but not the exact material type for the application
Power of 1000 W for oven	20	Based on product specifications, but not the exact oven used

Figure 119 - Assigned data quality uncertainties to assumptions used in sustainability calculations.

Application
Viability

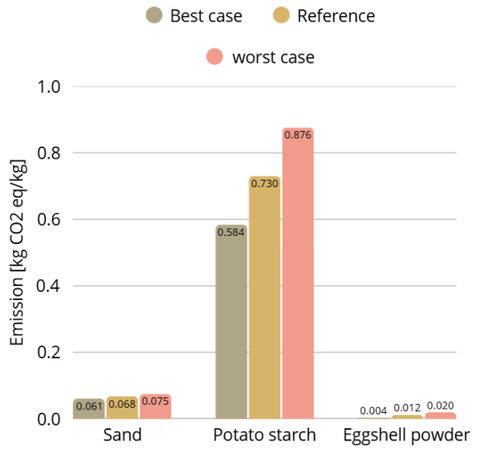


Figure 120 - Total emissions of Agristone ingredients together with best and worst case scenario.

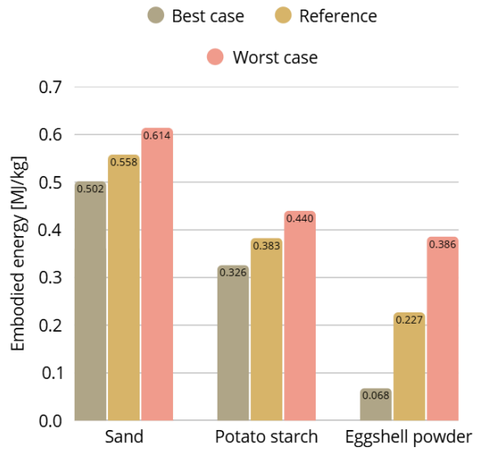


Figure 121 - Total embodied energy of Agristone ingredients together with best and worst case scenario.

confidently say that Agristone has lesser impact. It is assumed that Agristone is the preferred option considering sustainability.

Costs

To evaluate the viability of Agristone as an alternative to conventional precast concrete blocks, a preliminary cost estimation was made based on the material composition. The same volume and density are used as well as the same percentage in mass per ingredient.

Two separate calculations will be conducted, with and without pigments. The percentages per weight of Agristone with pigments are shown in Figure 122.

-Raw material assumptions

Potato starch retail prizes in The Netherlands in 2025 range between €0.44/kg and €1.06/kg (Average of €0.75/kg) (Selina Wamucii, 2020c). Sand can be bought for about €0.04/kg (Bigbag Metselzand 0-3mm, z.d.). Eggshell powder was currently bought at €10/kg, but in bulk this price should lower drastically. Argo-based wastes used as cement replacements have already proven to be less expensive than industrial by products (Sathiparan, 2021) and research has shown that using eggshell powder as a partial cement replacement can lower the overall cost of the product with a reduction of 5.3% with a 7.5% eggshell incorporation as replacement (Shah & Bhat, 2024). An eggshell powder cost of €0.15/kg is estimated. The cost of the demi-water will be ignored due to the negligible low prizes. The cost of the oxides range around €40/kg when order in small quantities. It is estimated that this prize will lower in bulk with maybe 37.5%. This is a relative low prize drop for bulk retail due to the limitations of scaling up for a windmill. Therefore a cost estimation of €25/kg will be used.

The same data quality levels are used for this calculation to be able to simulate the uncertainties. The uncertainties are shown in Figure 123.

-Total values per block

Figure 124 shows the total estimated cost per block for both material options. Figure 125 shows the same estimations, but now comparing pigmented Agristone with concrete. Agristone, with or without pigments, has a higher cost. The best case scenario for Agristone still costs more that the worst case for concrete. Pigmented

Ingredients Agristone	Percentage (%)	Weight per block (kg)
Sand	61.24	6.61
Potato starch	13.89	1.50
Demi water	14.81	1.60
Eggshells	8.75	0.95
Pigments	1.31	0.14

Figure 122 - Calculated weigth per ingredient in an Agristone block with oxide pigments.

Assumption	Uncertainty (%)	Justification
Cost Potato starch €0.75/kg	15	Live bulk prizes in NL
Cost sand €0.04/kg	10	Bulk retail prize
Cost eggshell powder €0.15/kg	70	Based on well know material database
Cost pigments €25/kg	70	Based on well know material database
Cost structural lightweight concrete €0.89/block	10	Retail prize

Figure 123 - Assigned data quality uncertainties to assumptions used in costs calculations.

Application
Viability

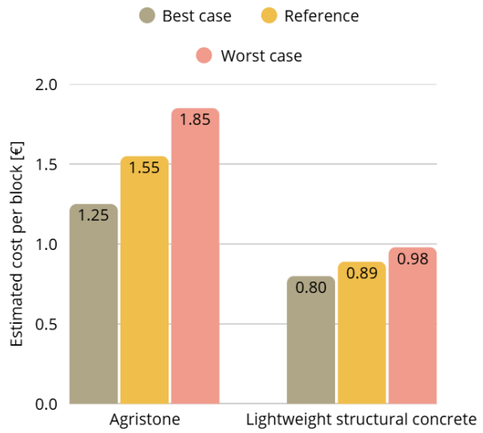


Figure 124 - Estimated cost of Agristone and lightweight structural concrete block together with best and worst case scenario.

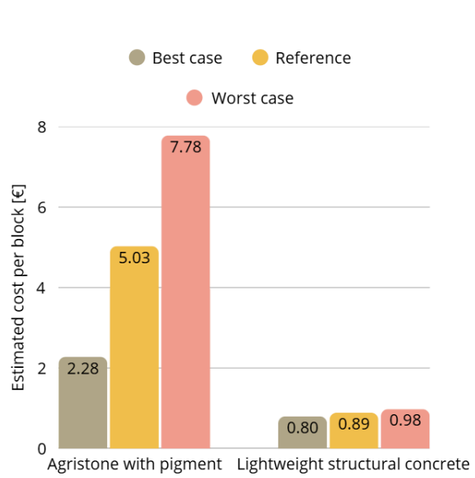


Figure 125 - Estimated cost of pigmented Agristone and lightweight structural concrete block together with best and worst case scenario.

Agristone is estimated be quite expensive and is estimated, in the worst case scenario, to reach costs of €7.78 per block

-Ingredient contribution

Figure 126 and 127 show the contributions of the different materials in Agristone to the total cost of an Agristone block. Without pigments, it is estimated that potato starch contributes a significant amount to the total cost of the material. Although the high uncertainty level for eggshell powder, it has the lowest impact on the total cost. Only when comparing the worst case scenario of eggshell powder and the best case scenario of sand, are their contributions similar. For the pigmented Agristone, the pigment is the main contributor to the cost.

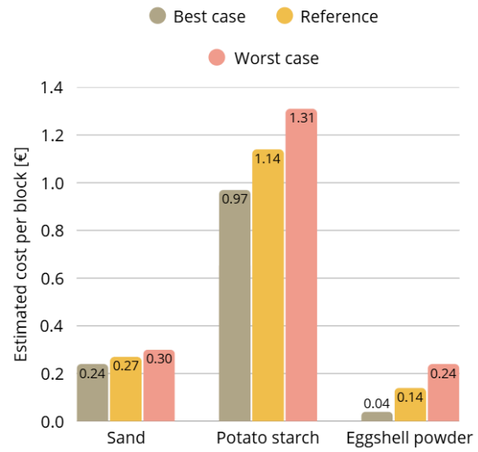


Figure 126 - Estimated cost of Agristone block ingredients together with best and worst case scenario.

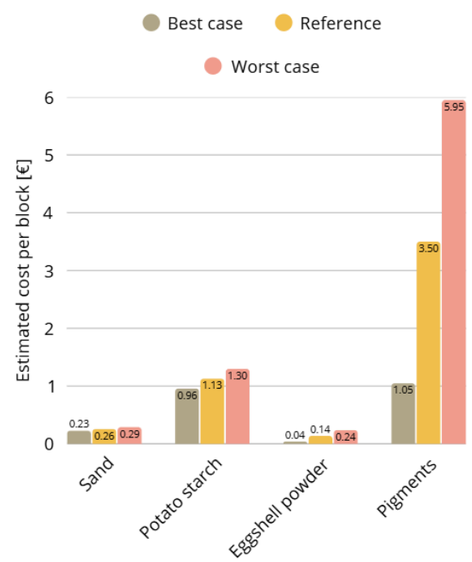


Figure 127 - Estimated cost of pigmented Agristone block ingredients together with best and worst case scenario.

-Conclusion

Agristone without pigment is expected to be more expensive per block than conventional concrete (€0.89). Argristone does perform well against benchmarked competing materials like Hempcrete (€3.31) (Hempcrete Blocks, 2025). Rammed Earth is not quite as expensive in material costs, but it is assumed that the installation costs of Argistone will make it the preferred option regarding costs. Agristone has the most potential to be less expensive, by finding an alternative to potato starch.

Discussion

-Life cycle stages

The calculations presented here only cover the material production and heating phases (cradle-to-gate). Other life cycle stages, such as transport, construction, usage, and end-of-life, may significantly affect the total energy use and CO_2 emissions. Including these stages could alter the comparative sustainability assessment.

-Influence of lab-scale production

The Agristione blocks are currently in the laboratory development stage, while conventional concrete is produced at industrial scale. Lab-scale production often has lower efficiency and higher energy per unit due to small batch sizes, while industrial-scale production may benefit from economies of scale and process optimization. This difference can influence the measured used energy and CO_2 emissions.

-Source of energy

If fossil fuels are used to provide the energy for heating and production, the CO_2 footprint increases. Switching to renewable electricity or heat can significantly lower emissions and improve the overall sustainability performance. In that case, the typical energy use of pre-cast concrete can be partly offset when green energy is applied in the process.

-Eggshell powder assumptions

In this study, limestone ($CaCO_3$) was used as a substitute for eggshell powder, because no life cycle data on eggshells was available. This comparison is not ideal, as the production of the two materials differs greatly. Limestone is obtained by quarrying and processing virgin rock, while eggshell powder is a by-product of the egg industry that mainly requires cleaning, drying, and grinding. To fully understand its impact, more detailed data on eggshell processing would be necessary.

-Other costs

The comparison of these costs ignore the influence of labor, management, research etc. These are costs that are needed for producing these blocks. It can be assumed that the product cost of Agristone will further increase with these additions.

-Costs of pigments

The current pigments costs are estimated to significantly increase the total cost of Agristone blocks. Either alternatives have to be found for pigments or a new application should be established, focussed on high-end and/or personalised goals where a higher cost is justified.

Application
Feasibility

Apart from the mechanical and material properties that are already addressed elsewhere, this section discusses other forms of feasibility, such as the manufacturing process and raw materials, analyzing how Agristone can be produced at scale and what resources are required. Exploring feasibility is important to ensure that promising concepts can transition into functional solutions for the construction industry.

Manufacture method

The current production process of the material uses oven-baking at relatively low temperatures (approximately 120 °C for two hours). This lower thermal requirement suggests that scaling up is technically straightforward, since larger ovens or continuous oven systems could be employed to accommodate higher production volumes. The process does not depend on extreme heat, making it easier to reproduce at industrial scale.

One current limitation lies in the separation of the baked mix into chunks before pressing. Currently, this step is labor-intensive and would need to be automated to enable efficient large-scale production. Automation in this stage would significantly improve throughput and consistency.

The current curing time is at least 21 days for which storage space is needed. When working in bulk, this could result in high costs.

The pressing of the material can also be automated. however, it requires specialized equipment. To press multiple bricks simultaneously, several custom-made steel molds are necessary, which represents a considerable upfront investment. Despite these initial costs, once the pressing system and molds are in place, it is assumed that production becomes efficient, scalable, and relatively inexpensive per unit.

-Conclusion

The low temperature baking process provides a strong foundation for scalability. while the main challenges relate to automating labor-intensive steps, facilitating storage space for curing and investing in pressing equipment, large-scale production seems technically and economically feasible. However, the need for storage space for curing could be a bottle neck.

Raw material sources

Although sand is a finite raw material, the material is currently widely available for use in material production. It is used for many construction materials like concrete and glass. Although the material is widely available, the increasing demand creates higher needs than sand can be replenished (Cao et al., 2025). It is assumed that the use of sand is feasible for now, but that an alternative raw material would be preferred.

Only in The Netherlands, about 20,000 to 40,000 metric tons of eggshells yearly, end up in landfill (Eggshell-based Ceramics and Bioplastics - MaterialDistrict, 2025). Using these eggshells only for Agristone producion (block of 30 x 10 x 20 with density of 1800 kg/m3), about 40,000,000 blocks can be produced per year. Assuming that a low-rise building uses about 5,000 concrete blocks, including slight material losses and based on the calculation in Figure 128, 8,000 buildings can be build using Agristone yearly. This is only considering eggshell waste in The Netherlands. With these calculations, it is assumed that waste-based eggshells create a big enough waste-stream to use as ingredient in building blocks without creating a demand in eggshell waste. These calculations only work when the rate of eggshell waste stays the same over time.

To create a low-rise building with 5,000 blocks, about 7,600 kg of potato starch is needed, meaning that for 8,000 of these low-rise buildings, about 60,000 metric tons of potato starch is needed. The Netherlands exports about 185,000 metric tons of potato starch (European Export of Potato Starch by Country, 2023, 2024), showing their high surplus of this raw material. Although the raw material seems available in The Netherlands, Agristone does have to use a large portion of Dutch production, making the feasibility of the material questionable.

to create 5,000 blocks for 8,000 buildings of Agristone with an oxide color, 5,600 metric tons of oxide pigment is needed (Earth Colours Containing >=70% Iron(III)Oxide Imports From Spain |2023, n.d.). In 2023, the Netherlands imported about 270 metric tons of red oxides from Spain. If all these oxides would be used for Agristone, only 385 buildings could be build which is about 5% of what can be build using the plain Agristone blocks.

-Conclusion

The raw materials required for Agristone are widely available within the Netherlands. However, for potato starch and sand, questions remain regarding the extent of resource depletion, highlighting the need for further research. Based on current estimates, Agristone could supply material for approximately 8,000 low-rise buildings per year. Considering the Dutch government's target of 900,000 new homes, this would translate into a construction timeline of roughly 11 years if Agristone were used exclusively, assuming that its emissions remain low enough to comply with nitrogen regulations.

When introducing the pigmented Agristone options, the amount of buildings that can be build are limited. This suggest that the pigmented Agristone options should be considered for specific applications instead of as the main structural material of a building.

Can 8000 houses be build yearly	Sand	≈
	Eggshell powder	✓
	Potato starch	≈
	Pigment	✗

Assumption	Calculation		
10 m by 6 m floor plan	circumference of 32 m	32 m circumference x 3 m hight x 3 floor levels = 288 m^2	288 m^2 / 0.06 m^2 = 4800
3 floor levels			
level hight of 3 m			
Agristone block area of 0.3 m by 0.2 m	0.06 m^2		

Figure 128 - Calculation to estimate the amount of pre cast blocks in a low-rise building when used as inner leave wall.

Conclusion 8

Conclusion
Research questions

In this chapter, I present the conclusions of the study by answering the research questions. Each question is discussed in turn, summarizing the key findings and what they mean for the study.

Research question 1
"How can CoRncrete's water resistance be improved to meet architectural needs in wet or humid environments?"

With a change in the manufacturing method and the replacement of 12.5% of sand with eggshell powder, the new Agristone is able to withstand water exposure without fully dissolving for at least 24 hours. In contrast, the original CoRncrete samples did not last longer than 10 minutes. The addition of eggshell powder also results in a slightly higher UCS, making this modification a assumed improvement.

These results are promising; however, a significant decrease in strength was observed when the samples were exposed to water for extended periods. This makes it difficult to determine how the material's water resistance could be improved to meet architectural standards.

Research question 2
"What design characteristics make CoRncrete suitable and desirable for use as a precast architectural block?"

Although the sample changed slightly in appearance and changed in name (CoRncrete to Agristone), the same question still applies.

The visual and surface differences between the samples introduced distinct opportunities for architectural expression. The plain sample was perceived as neutral, calm, and stable, making it suitable for applications where the block must remain in the background and serve as a quiet, grounding element in a space. The marbled sample was described as curiosity-inducing and playful, stimulating a wide range of imaginative and affective responses. Its patterned quality suggests potential for use as a focal point or accent feature, where engagement and exploration are desirable. The pigmented sample occupied a middle ground, combining the stability of the plain surface with additional interpretive and symbolic potential. This balance makes it particularly suited for adding character and atmosphere to a room without dominating it.

Together, these findings highlight that the design characteristics of CoRncrete, neutrality, pattern, and pigmentation, allow the material to function across a spectrum of architectural roles, from background surface to focal element. This versatility ensures that CoRncrete is not only technically suitable for use as a precast block, but also aesthetically and experientially desirable, broadening its potential in architectural applications.

Its shape makes it easy to implement in current building practises, since it is similar to current pre-cast concrete blocks, and therefore makes the block desirable for use.

Conclusion
Requirements & wishes

Requirement 1
Not yet fully determined, as the climate chamber tests did not provide reliable results due to setup issues. However, immersion tests indicate that a sample can survive for 24 hours, submerged in water. Still, the samples lost on average 85.75% of its UCS, which is allot. It can be assumed that Agristone can withstand certain amounts of water exposure, but cannot yet keep structural integrity after consistent high amounts of water exposure.

Requirement 2
One of the samples (12.5% sand replacement with eggshell powder) showed an average strength of 13.97 MPa (n=3). This indicates that Agristone can meet the requirement of 13 MPa. Still, the margin is small, so further optimization is advised to make sure all blocks consistently reach or exceed this level.

Requirement 3
As shown in the viability chapter: 3.868 MJ vs. 9.828 MJ energy demand and 0.810 kg CO_2 eq vs. 1.464 kg CO_2 eq, demonstrating an assumed improvement in sustainable performance.

Requirement 4
This agristone blocks are not specifically designed for ease of disassembly yet. However, with the application of mortar innovations, this requirement could still be achieved. This remains a point for further development.

Requirement 5 + 6
For Dutch building norms, the required insulation performance can be reached within a wall thickness of 40 cm.

Requirement 7
Agristone is currently expected to be slightly more expensive than conventional concrete, but cheaper than hempcrete and, when labor is included, also cheaper than rammed earth. Geopolymers, however, remain more cost-effective, even compared to conventional concrete.

Requirement 8
The production steps for Agristone are relatively simple, requiring little specialization. The process can be largely automated and applied on-site using methods familiar to construction workers handling conventional concrete blocks.

Wish 1
Same status as Requirement 1. Testing is not yet conclusive, but initial immersion results are promising.

Wish 2
This wish is not fully achieved. While the product contains biobased components, sand is still required, preventing it from being 100% biobased.

Wish 3
As described in the desirability chapter, multiple options in color and finish are possible.

Wish 4
As with Requirement 5 and 6, the Passive House standards can be reached within the 40 cm wall thickness.

Achieved

Not achieved

Indecisive

Requirements

1- CoRncrete must resist an environment with 60% RH and 30 degrees for 24 hours without structural failure.

2- Must fall within a strength class of at least 13 MPa.

3- The material must result in lower CO_2 emissions and less energy use than traditional Portland Cement pre-cast concrete.

4- The product must be designed to allow for easy disassembly and reuse of components.

5- The material must function within a total wall thickness of max. 40 cm.

7- The complete wall assembly, including the material, must achieve an R-value of at least 4.7 m^2K/W (Isodirect B.V., 2023).

8- The cost per unit (brick/block) should be competitive with other sustainable concrete alternatives (e.g., hempcrete blocks, geopolymer blocks), ideally not exceeding their average market price.

9- The production process should require fewer steps or less specialized labour than rammed earth or bio-cement production.

Wishes

1- CoRncrete must resist an environment with 80% RH and 30 degrees for 24 hours without structural failure.

2- Develop a fully circular product with the use of biobased or waste stream materials.

3- The product should offer a line extension with multiple aesthetic options (e.g., variations in colour or texture).

4- The complete wall assembly, including the material, must achieve an R-value of 6.7 m^2K/W, suitable for passive houses (Passive House Institute Dr. Wolfgang Feist, n.d.-b).

Conclusion
Closing statement

Agristone shows that sustainable building materials can combine structural reliability, environmental responsibility, and practical usability. With a compressive strength of 14 MPa and the ability to withstand at least 24 hours of water exposure, it meets the requirements for load-bearing inner-leaf walls in low-rise buildings. Its form and use are identical to conventional pre-cast concrete blocks, which makes implementation straightforward and familiar for builders. Compared to standard concrete, Agristone reduces embodied energy by 60% and CO_2 eq emissions by 45%. At the same time, annual production could be sufficient to build as many as 8,000 homes. Although costs are higher than conventional concrete blocks, they are comparable to other sustainable alternatives and are balanced by fewer construction steps and aesthetic options.

The key advantages of Agristone, summarized in Figure 129, highlight its potential to act not just as a technical replacement for concrete blocks, but as a forward-looking material that combines strength, sustainable advantages and aesthetic freedom.

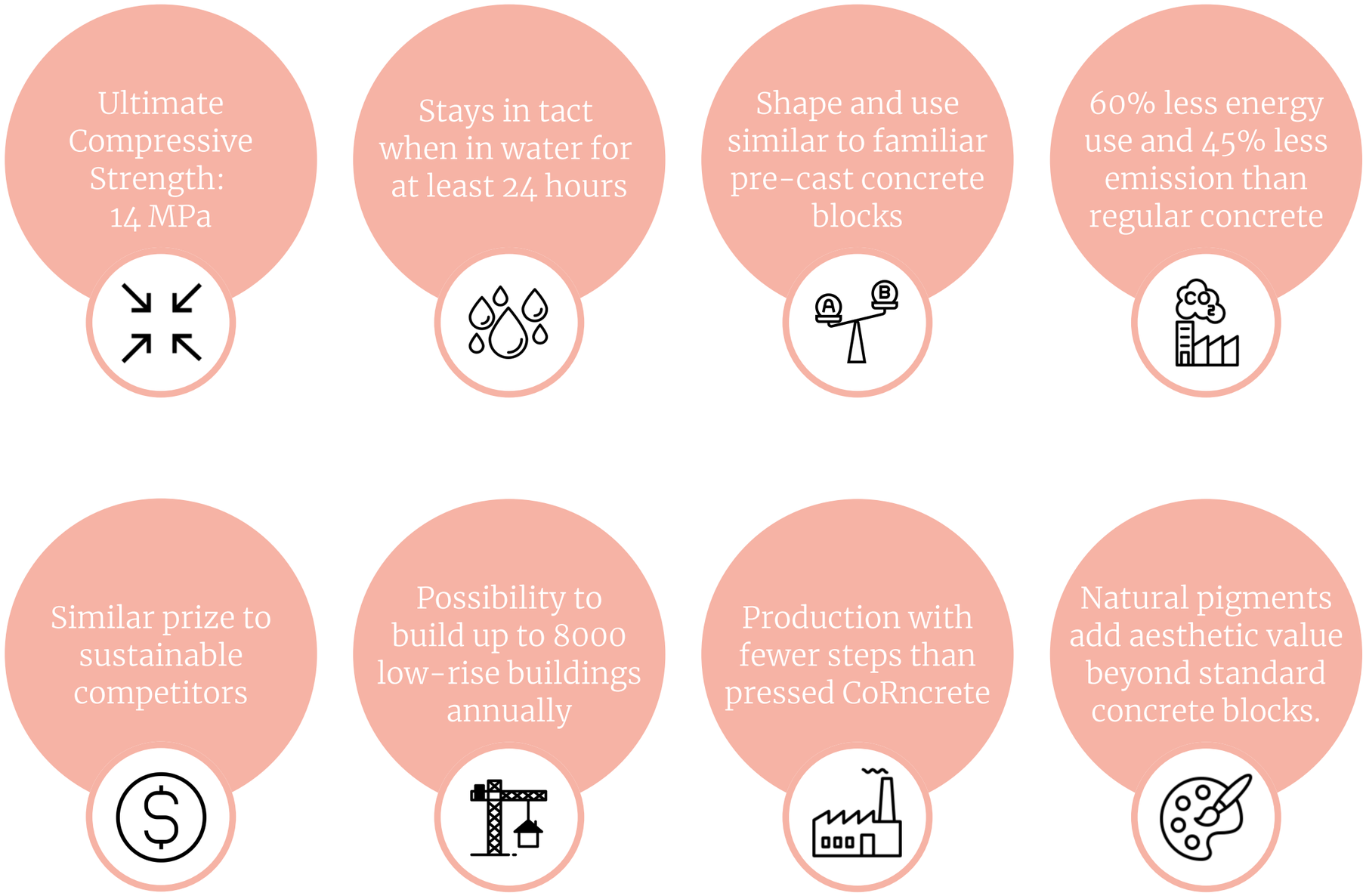


Figure 129 - Overview of Agristone's key advantages.

Recommendations 9

Recommendations
Future studies

While this study has provided valuable insights into the potential of CoRncrete as a precast architectural material, several areas remain open for further investigation. This chapter introduces possible directions for future studies, ordered by relevance to the product's development stages.

Water resistance testing
The initial water resistance tests should be repeated with improved procedures, including longer drying periods for the samples and extended exposure in climate chambers. This might yield more reliable data on long-term durability. This could give information that can be used for optimizing the use of eggshell as an additive.

Strength loss after water immersion
Another important point for research is the loss of strength after water exposure. One possible reason is that the starch binder partly dissolves, reducing cohesion within the block. For applications like façades or other uses with more moisture exposure, this effect needs to be better understood.

Dissolving starch in samples
Although the water resistance improved, there are still traces of the potato starch dissolving (slimy outside of samples in water). Additional research should be done to solve this issue by, for example, doing research in stabilizers and crosslinking agents or further research into sealers.

Changing the manufacture method
Changing the manufacture method seemed to have to most influence on the water resistance of the samples. This suggests that more research and/or tinkering in the direction of manufacture options and changes, could reveal more benefits for water resistance or other properties of Agristone.

Influence of pigments
It remains unclear whether the use of the color pigments, affects the mechanical or durability performance of the material. Future studies should examine whether pigmentation lowers the performance of the Agristone in all technical aspects.

Low elastic modulus
This report concluded with a material with a relatively low elastic modulus. A low elastic modulus is considered to be more flexible and less suited for use in load-bearing applications. Further research into the structural integrity of Agristone, with concern for the elastic modulus would be necessary for final determination of the materials feasibility.

Comprehensive technical testing
To fully assess the suitability of CoRncrete for construction applications, a complete set of standard building material tests should be carried out. These include but are not limited to: freeze–thaw resistance, chemical resistance, thermal insulation capacity, and fire resistance. Such data are essential for bench marking against existing construction materials and for certification processes.

Material impact assessment
More research is needed to understand the broader impact of CoRncrete. This should include life cycle studies, carbon footprint calculations, and an assessment of how the material could contribute to sustainable construction at a larger scale.

Scaling up production
Further research is required into the challenges of scaling up the manufacturing process. Optimization of the production chain, automation of currently labor-intensive steps, and the development of cost-efficient molds and pressing techniques will be crucial for industrial viability.

Design for reuse
The block design could be further refined to support reuse and circularity. Ideas like dry stacking or interlocking systems would make it easier to take structures apart and recover materials, which would contribute to more sustainable building methods.

Material substitution
It may also be worthwhile to look at alternatives for sand, such as bio-based or less scarce materials. Using these substitutes could lower the environmental impact and reduce the dependence on non-renewable resources.

Increase material strength
Future work should also explore ways to raise the compressive strength. Some of the tested samples already come close to the required 13.5 MPa, but more optimization is needed to consistently reach this level. If the strength can be improved further, the blocks could also be used in bigger projects, not just low-rise buildings.

Reflection

Reflection

After graduating for 20 weeks, I learned many new things. Reflecting on these lessons helps to actively engage with what is learned to eventually create new skills and grow in my professional career as well as grow as a person. In this chapter I will highlight 3 topics to which I reflect.

Conducting research for the first time

This project gave me the opportunity to conduct independent research for the first time, rather than focusing solely on design tasks. My earlier exposure to research during a bachelor internship in food technology initially gave me confidence, yet as the work progressed, more unforeseen challenges emerged, leaving me at times feeling inadequate. These moments taught me that uncertainty and mistakes are integral to the learning process and even indicate that I am beginning to recognize gaps in the research. Looking back, I see that I tended to respond hastily under stress, which increased the likelihood of errors. In future projects, I aim to embrace the idea that making mistakes does not diminish my expertise but instead supports growth. Allowing myself space to experiment and calmly address problems will help me refine my research skills and approach new questions with greater confidence.

Maintaining a calm mental state

Throughout this graduation project, I managed to maintain a remarkably calm and positive state of mind. In the past, stress often undermined my focus and enjoyment, but this project encouraged me to plan ahead and work steadily, which created a reassuring sense of progress. Support from my supervisors also helped me stay grounded and quickly put doubts into perspective; their belief in my abilities was both motivating and reassuring. This experience showed me that structured work habits, timely communication, and actively seeking support are powerful strategies for sustaining a healthy rhythm. I intend to carry this newfound calm and satisfaction with my work into my professional life, ensuring that even under pressure I can remain attentive and enjoy the process.

The importance of a network

Over the course of this project, I realized how valuable the network I have built around the built environment has become. My decision to follow courses in architecture, join a committee in one of its associations, and position my graduation topic in this field stemmed from a clear goal: I wanted to bridge the gap between my design background and the building sector, and to position myself as a designer who understands materiality and construction beyond traditional product design. By deliberately taking these steps, I unintentionally created a circle of experts and like-minded designers. Their willingness to share knowledge enriched my understanding of building materials and structural challenges and provided motivation whenever the research became complex. Beyond that, I greatly enjoyed getting to know these enthusiastic people, which added a personal dimension to the work. This experience highlighted that professional growth is closely tied to social connection. I plan to continue investing in lasting relationships within my field: keeping in touch, seeking out new encounters, and sharing my own expertise so that the network remains reciprocal and supports my ongoing development.

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Figure 4: Typical stress-strain curve for concrete [45]. (n.d.). ResearchGate. https://www.researchgate.net/figure/Typical-stress-strain-curve-for-concrete-45_fig4_315716360

Appendices

Appendix A
Technical characterization results

	Elastic modulus	Yield strength	UCS	Deformation
-O	0.22 GPa STD 0.04	10.77 MPa STD 1.08	11.02 MPa STD 1.21	7.41 % STD 0.23
-A	0.11 GPa STD 0.01	5.03 MPa STD 0.91	5.31 MPa STD 0.83	8.14 % STD 0.85
-B	0.09 GPa STD 0.02	3.81 MPa STD 0.34	4.23 MPa STD 0.38	8.34 % STD 0.54
-C	0.02 GPa STD 0.01	1.29 MPa STD 0.46	1.36 MPa STD 0.42	8.73 % STD 0.54
DO	0.25 GPa STD 0.06	11.35 MPa STD 1.48	12.29 MPa STD 1.97	7.76 % STD 0.21
DA	0.10 GPa STD 0.02	3.97 MPa STD 0.82	4.48 MPa STD 0.98	8.26 % STD 0.34
DB	0.06 GPa STD 0.02	2.40 MPa STD 0.23	2.77 MPa STD 0.38	8.70 % STD 0.47
DC	0.08 GPa STD 0.01	3.51 MPa STD 0.21	3.82 MPa STD 0.38	8.95 % STD 0.51
HO	0.35 GPa STD 0.10	10.52 MPa STD 0.91	12.99 MPa STD 1.36	6.74 % STD 0.55
HA	0.12 GPa STD .0.03	4.96 MPa STD 0.90	5.43 MPa STD 0.99	8.96 % STD 0.44
HB	0.09 GPa STD 0.02	4.26 MPa STD 1.80	4.63 MPa STD 1.43	9.35 % STD 1.16
HC	0.09 GPa STD 0.01	4.10 MPa STD 0.50	4.64 MPa STD 0.52	9.02 % STD 0.71
PO	0.21 GPa STD 0.01	9.85 MPa STD 0.24	10.21 MPa STD 0.24	7.17 % STD 0.36
PA	0.08 GPa STD 0.02	4.42 MPa STD 0.59	4.72 MPa STD 0.49	9.48 % STD 0.36
PB	0.10 GPa STD 0.01	4.54 MPa STD 0.40	4.98 MPa STD 0.55	9.80 % STD 0.48
PC	0.12 GPa STD 0.04	4.96 MPa STD 1.28	5.56 MPa STD 1.78	9.46 % STD 0.29

Figure X - Results climate chamber test.

	Elastic modulus	Yield strength	UCS	Deformation
EO	0.25 GPa STD 0.04	12.41 MPa STD 1.05	12.98 MPa STD 1.29	6.82 % STD 0.06
EA	0.20 GPa STD 0.03	11.11 MPa STD 1.49	12.26 MPa STD 1.83	7.65 % STD 0.18
EB	0.23 GPa STD 0.02	11.92 MPa STD 1.64	12.93 MPa STD 1.51	7.18 % STD 0.76
EC	0.28 GPa STD 0.05	13.30 MPa STD 0.76	13.97 MPa STD 0.92	7.25 % STD 0.58

Figure X - Results extra long curing test.

	Elastic modulus	Yield strength	UCS	Deformation
O-1	0.20 GPa	10.05 MPa	10.96 MPa	8.10 %
O-2	0.06 GPa	2.57 MPa	2.84 MPa	7.99 %
7.5-1	0.13 GPa	5.73 MPa	6.35 MPa	9.29 %
7.5-2	0.01 GPa	0.45 MPa	0.48 MPa	10.59 %
10-1	0.16 GPa	9.13 MPa	9.89 MPa	8.62 %
10-2	0.03 GPa	0.99 MPa	1.31 MPa	8.55 %
12.5-1	0.14 GPa	7.81 MPa	8.62 MPa	9.10 %
12.5-2	0.01 GPa	0.79 MPa	0.83 MPa	10.09 %

Figure X - Results additional submerge test usual cylinders.