Designing Permeable Grid Pavement: Integrating Stakeholder Needs and Sustainable Materials

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Abstract

Urbanisation in combination with climate change threatens human life through the Urban Heat Island effect and Urban Flooding. Grid Pavement replaces impervious pavement by a combination of vegetation and infrastructure, creating climate adaptive urban areas with crucial infrastructure. However, current Grid Pavement materials have a detrimental effect on the environment. This study investigates sustainable materialisation of Grid Pavement, and demands of stakeholders, combining technical with human-centered material development.

This research consists of five analyses, contributing to a holistically improved Grid Pavement design. Stakeholders were interviewed to reveal key stakeholder and design requirements and wishes. The Grid Pavement market was analysed for design requirements and wishes. From current Grid Pavement materialisation and sustainable strategies an alternative material is identified. Tinkering was done to get a complete understanding of the material under varying conditions. To understand the user experience of the material, experiential characteristics were identified through stakeholder interviews. An understanding of the material mechanical properties was gained through material testing. The final concept was designed to enhance the material's experiential characteristics, while a Finite Element Analysis ensured structural integrity.

Stakeholder interviews identified Municipalities and (Landscape) Architects as key stakeholders. CoRncrete poses a potential sustainable material alternative for Grid Pavement. Forming CoRncrete in the hydraulic press using 0.250 to 0.500 mm sand grains produces the highest quality, while ensuring scalability and sustainability of the material. The user experience of CoRncrete is heavily dependent on the visibility of the sand grains. CoRncrete containing 0.250 to 0.500 mm sand grains is an ordinary, recognisable material, while its natural appearance can improve the sustainable perception of Grid Pavement, posing a competitive advantage compared to concrete and plastic. Additionally, visible sand grains provided a fascinating tactile experience, inviting curiosity and attraction. CoRncrete formed in the hydraulic press, containing 0.250 to 0.500 mm sand grains and potato starch, called PMP-CoRncrete, poses the optimal material composition for Grid Pavement. PMP-CoRncrete exhibits a Young's modulus of 660.40 MPa, a Yield Strength of 25.97 MPa and an Ultimate Compressive Strength of 27.05 MPa and a density of 1823 kg/m^3. Combining the Young's Modulus and density shows PMP-CoRncrete is comparable to polymers, while being heavier than natural materials and having a lower Young's Modulus compared to composites. Curing time is found to significantly affect CoRncrete strength, where increasing the curing time from 2 to 9 days increases the UCS of potato starch-containing samples by 52.02%.

CoRnGrid is a CoRncrete Grid Pavement module that harmoniously integrates vegetation into infrastructure due to its design features and materialisation. One module measures 600 by 390 by 80 mm (L by W by H), weighs 23.26 kilograms and costs €12 to €15 per module.

This research pushes the boundaries of infrastructure materialisation while holistically advancing the development of CoRncrete, moving away from toxic material development, towards a sustainable future.

Preface

This project is an Integrated Product Design master graduation project at the Industrial Design Engineering faculty of the TU Delft.

This project started at The Green Village, a sustainable innovation area. Their work pushes sustainable design, inspiring current and future generations. I want to thank The Green Village for their persistent contributions, enthusiasm and courage towards the current issues the world faces.

Tonn opened my eyes to the world of Grid Pavement and designing in the public space. I want to thank them for their trust and innovative vision that lead to this project.

Grazie mille and خیلی متشکرم Stefano and Sepideh. Thanking you goes in one breath as you worked together as a team, keen to embrace and guide me in the previously unknown field of material development. Your keen feedback and extensive knowledge allowed me to push myself to my best performance. Simultaneously you were vulnerable, caring and sincere, putting me at ease when it was difficult and making me jump through the roof of enthusiasm when the project went well. I wish you both the very best in life and hope you face each challenge with the wisdom and heart I have come to know.

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1 introduction

Why is this research useful?
What does this research focus on?

Cities grow and become more densely populated as they attract young migrants from rural areas, incoming immigrants, and young adults starting families, offering numerous employment and educational opportunities (Centraal Bureau voor de Statistiek, n.d.). The expansion of cities and the increase of their population, known as Urbanization (European Environment Agency, n.d.), is expected to increase globally (Bettencourt & West, 2010) as well as in The Netherlands (Statista, 2024). Besides opportunities, urbanization impacts humanity negatively through noise, water, air and soil pollution, over-crowding, poor housing and climate change (Rizwan et al., 2008; Xu et al., 2014; Vardoulakis et al., 2016; Mentens et al., 2005;). Urbanization leads to the conversion of cropland, grassland, forests, wetlands, and wilderness – collectively referred to as vegetated soils – into impervious roads and structures, negatively contributing to the Urban Heat Island (UHI) effect and Urban Flooding (UF) (Figure 1).

The urban heat island (UHI) effect refers to the phenomenon where urban areas experience higher air temperatures compared to surrounding suburban and rural regions (Zoulia et al., 2008; Santamouris, 2013; Rizwan et al., 2008; Yang et al., 2015; Oke, 1973; Heaviside et al., 2014).

The urban temperature increase can reach up to 10 °C (Mihalakakou et al. 2002; Zoulia et al., 2008;). UHI's are caused by roads and urban structures capturing and releasing solar radiation, as well as decreased vegetation coverage and heat production by heat sources like cars and air conditions, intensified by changing weather patterns due to climate change (Figure 1) (Rizwan et al., 2008; Santamouris, 2013; Yang et al., 2015; Klok et al., 2012; Oke, 1973). UHI's increase air pollution and heat stress, while impacting the energy consumption of buildings, increasing the ecological footprint of the city (Santamouris et al. 2007; Hassid et al. 2000; Santamouris et al. 2001; Xu et al., 2014; Santamouris, 2013; Heaviside et al., 2014).

Impervious roads and structures increase stormwater runoff and decrease infiltration into sub-soils, causing floods in urban areas (Figure 1) (Ashley et al., 2005; Wheater & Evans, 2009; Liu et al., 2014; Mentens et al., 2005; Goonetilleke et al., 2005; Whitford et al., 2001; Sonebi et al., 2016). Increased frequency and intensity of precipitation and storms caused by climate change increase risks from UF (Villarreal et al., 2004; Foster et al., 2011; Wheater & Evans, 2009; Ashley et al., 2005; Liu et al., 2014). UF poses a threat to human life, damages properties and infrastructure, costing enormous amounts of money, accelerates erosion of natural waterways, and pollutes water reservoirs (Wheater & Evans, 2009; Hall et al., 2005; Liu et al., 2014).

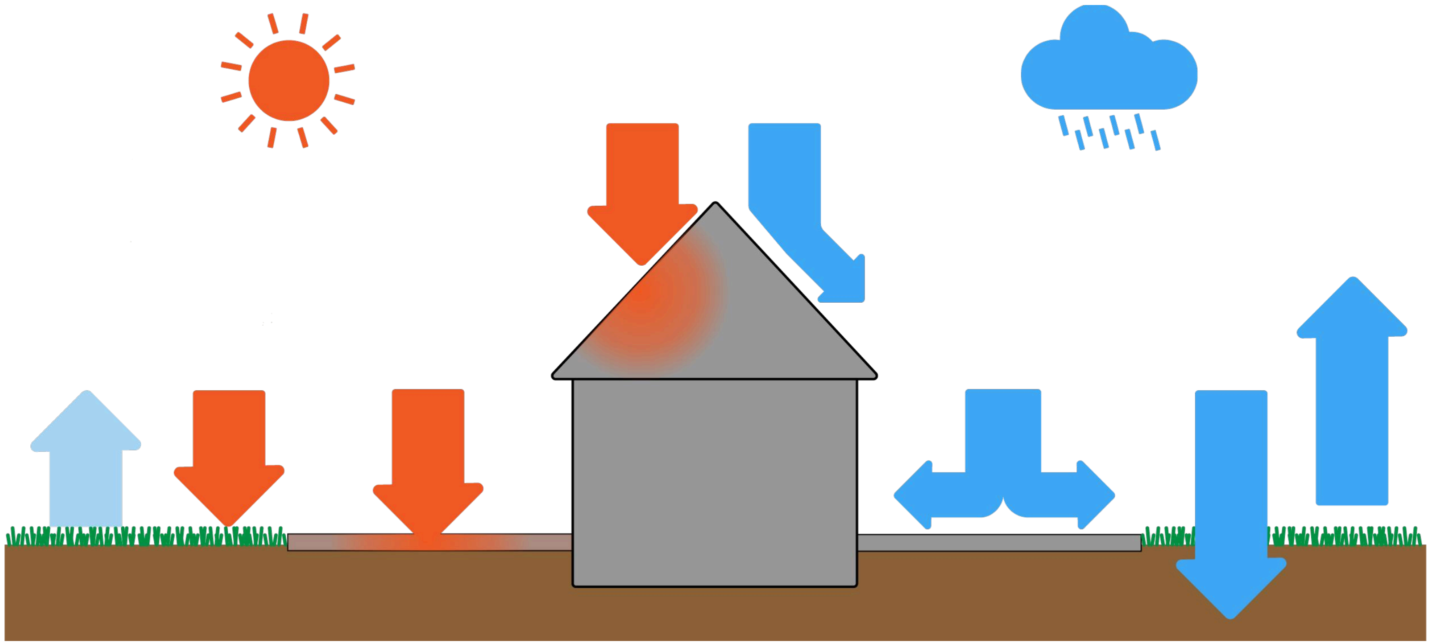


Figure 1: The effect of impervious pavement and urban structures on the Urban Heat Island effect and Urban Flooding

1.1 Permeable Pavement

Permeable pavement has emerged as a solution to mitigate the negative effects of impervious surfaces while providing surface hardening for essential urban infrastructure like roads, sidewalks, and car parks (Figure 2) (Tennis et al., 2002; Kuruppu et al., 2019; Shakrani et al., 2018; Mentens et al., 2005; Foster et al., 2011; Bhutta et al., 2012; Sonebi et al., 2016).

These pavement types allow water to permeate, drain and retain in their structure, mitigating UHI's and UF through filtration and evaporation of water (Kuruppu et al., 2019; Shakrani et al., 2018; Santamouris, 2013; Bhutta et al., 2012; Sonebi et al., 2016). Additionally, permeable pavement is capable of filtering harmful substances from stormwater and restoring groundwater supplies (Bhutta et al., 2012; Sonebi et al., 2016; Sansalone et al., 2008; Karim et al., 2014).

Permeable pavement can be categorized into porous pavement, modified asphalt or concrete, and systems consisting modular modules called interlocking pavers and Grid Pavement (GP) (Karim et al., 2014; Kuruppu et al., 2019; Shakrani et al., 2018) (Figure 3).

Cavities in the asphalt or concrete used in porous pavement provides the permeability whereas in interlocking pavers and GP the material is impervious but voids in the structure allow water to permeate (Karim et al., 2014; Sansalone et al., 2008; Shakrani et al., 2018). Porous pavement is suitable for both highways and low-traffic areas (Shakrani et al., 2018) and is the most used asphalt type on Dutch highways (Ministerie van Infrastructuur en Waterstaat, 2024), whereas interlocking pavers and grid systems are limited to low-traffic applications (Scholz & Grabowiecki, 2007). The permeable space in GP allows growth of vegetation, improving the hydrological and thermal performance through evapotranspiration as well as improving urban life, increasing biodiversity, and sequestering carbon (Rizwan et al., 2008; Santamouris, 2013; Foster et al., 2011; Shakrani et al., 2018; Alves et al., 2019).

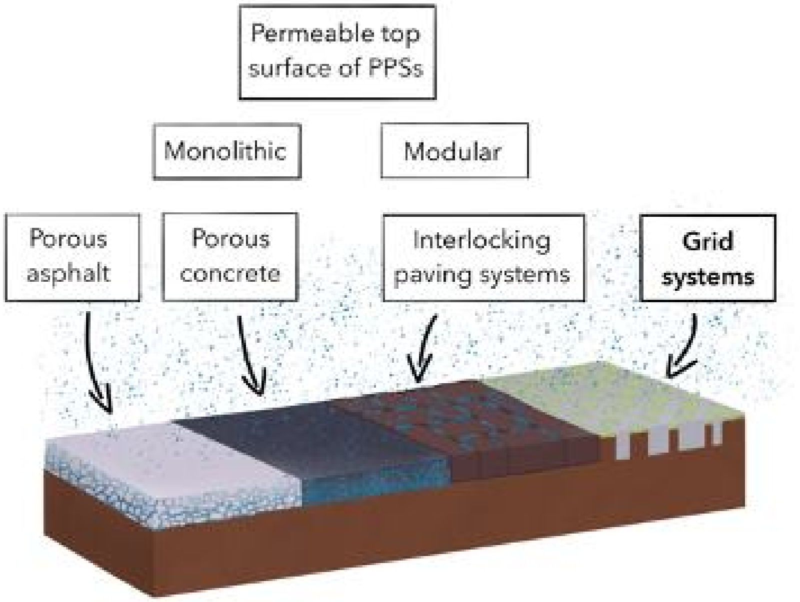


Figure 3: Different types of permeable pavement (Inspired by Kuruppu et al.,2019)

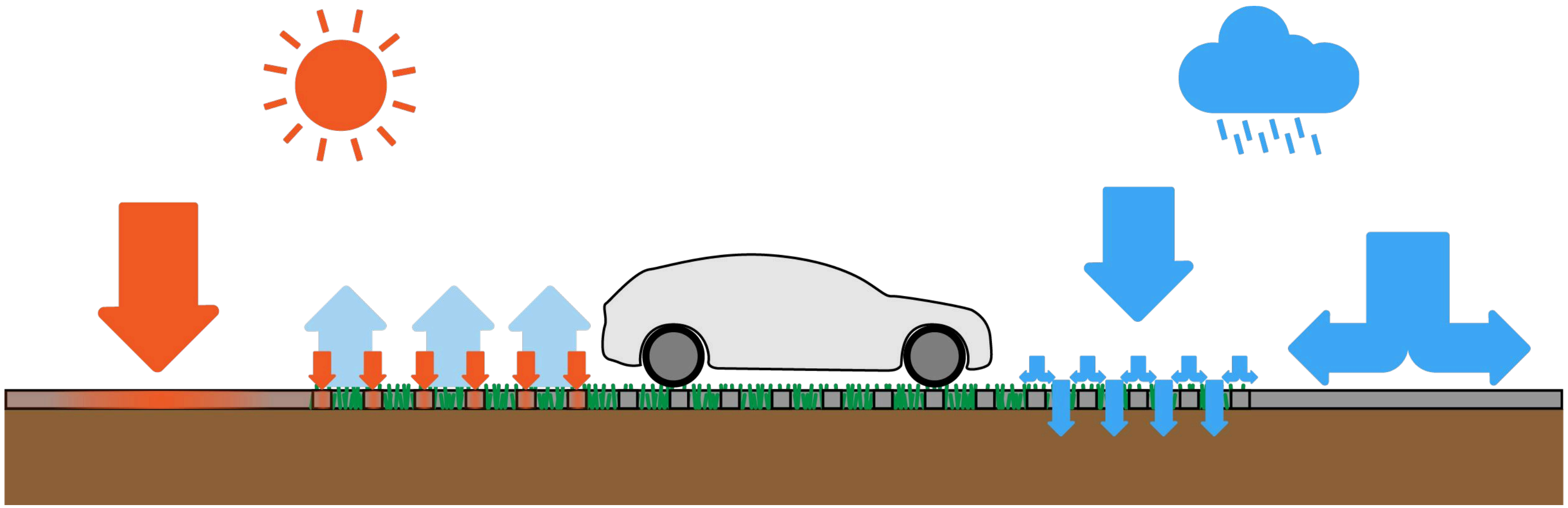


Figure 2: Permeable pavement as a climate adaptive solution for useful pavement without heat and water issues.

1.2 Tonn

Tonn is a Dutch company specialised in grass reinforcement solutions since 2013 (Tonn, 2024). They sell Grid Pavement called TAWWA GreenGrid (Tonn, 2023) (Figure 4). To reduce its carbon footprint, the TAWWA GreenGrid is made from recycled Polyethylene (PE) instead of virgin plastic and prioritizes local sourcing for both materials and production (Tonn, 2023). One module of the TAWWA GreenGrid measures 800 mm long, 600 mm wide and 80 mm high. The length and width allow the grids to be efficiently stacked and moved on standard Euro palettes or Display palette measuring 800 by 1200 mm or 800 by 600 mm, respectively (Logistiekdirect, n.d.; J. Heebink Transport, 2022). 80 mm is one of the standard heights of pavement bricks used in The Netherlands, avoiding extra elevation of the sub-soils when installing TAWWA GreenGrids in combination with brick pavement (Bestratingsweb.nl, n.d.; SlimBestraten.nl, n.d.). Each module is connected to the nect through an interlocking system. The top and left side of the TAWWA GreenGrids feature a connector, while the right and bottom side feature a hole shaped like the connector. This allows larger surfaces to be built through connecting multiple modules. This connection seeks to minimise movement between modules which could lead to structural failure and aesthetic disruption. To increase the rate at which vegetation grows in TAWWA GreenGrids, the open cells feature a gutter that is able to retain rainwater for the vegetation to use (Figure 5).

Tonn wants to improve the sustainability of their Grid Pavement. Since their company does not contain a technical department, collaboration was required, initiating this research. The aim of this research is to:

*Design **feasible** and **desirable** Grid Pavement*
*using a **sustainable** material*

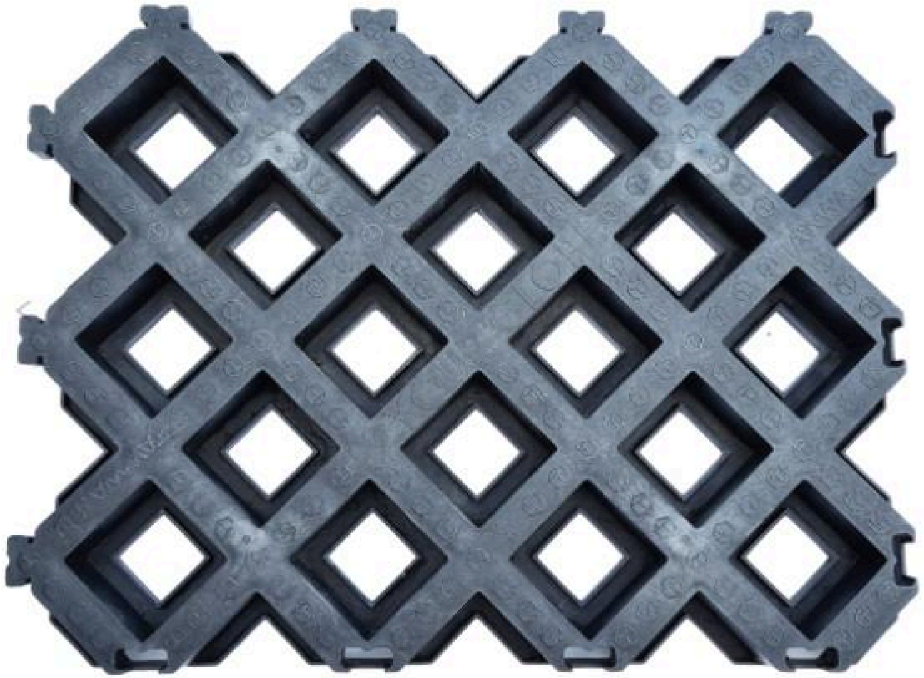


Figure 4: Tonn's TAWWA Grid (Tonn, 2023)

Figure 5: The gutter of TAWWA GreenGrids

2 method

What steps are taken to reach the design goal?
Why is each step taken?

This chapter explains the general research structure. Since multiple tests are conducted across different chapters, the methodology of each specific test is described in the relevant chapter.

2.1 Research Approach

The study aims at a holistic approach to material selection and development to design Grid Pavement (GP) from a sustainable material. To understand the context of sustainable materials and GP, interviews and market research are conducted. To accelerate the adoption of new materials and enhance user experience through their properties, application, and performance, both technical and human-centered advancements must be considered (Karana et al., 2015).

The Material Driven Design (MDD) method proposed by Karana et al. (2015) inspired the inclusion of a Tinkering, Technical Characterisation, and Experiential Characterisation phase (Figure 6).

The Context, Material and Tinkering phase were done simultaneously to gain comprehensive knowledge of both the material and its broader context. Technical and Experiential characterisation are carried out simultaneously, ensuring a holistic understanding of the material. Through a user experience vision and digital modeling, this understanding guides the development of a desirable and technically feasible GP redesign.

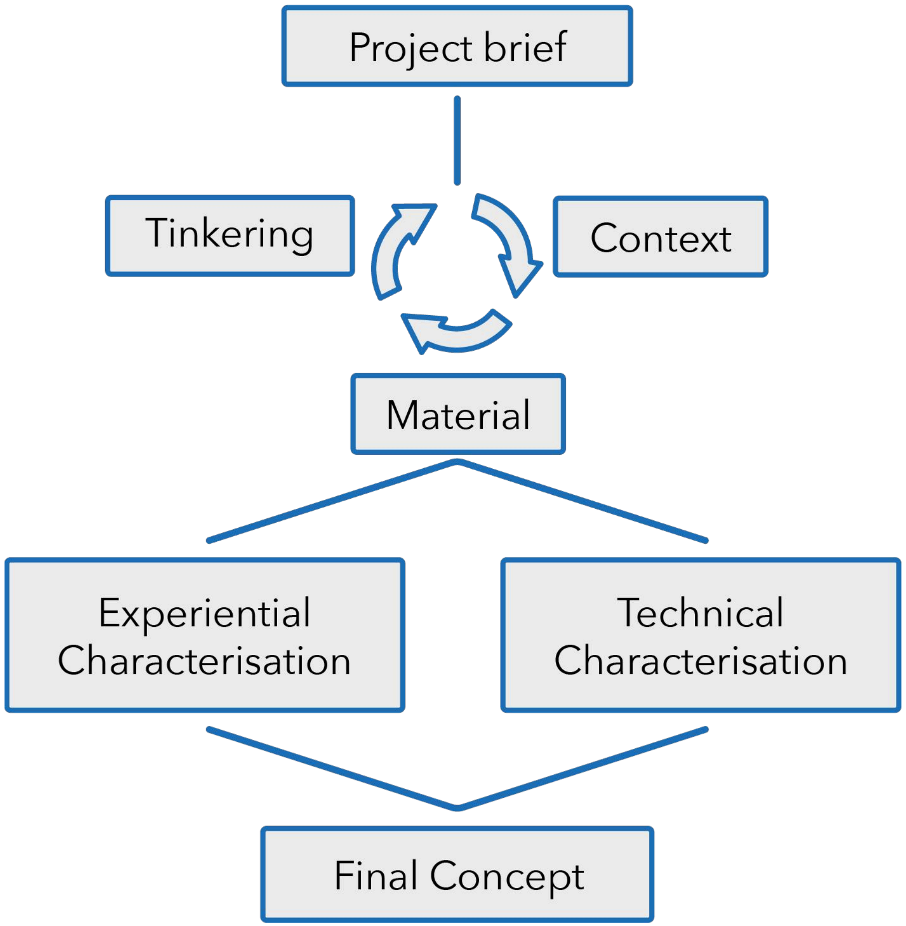


Figure 6: Project structure

Context

To understand the relationship between different stakeholders in the world of permeable pavement and their views on sustainable materialization, interviews were conducted. These interviews help define design requirements and assess stakeholder influence over the design process of the public space. Key stakeholders are identified for inclusion in the Experiential Characterisation phase. Additionally, the current market for Grid Pavement (GP) is analysed to identify trends and opportunities in GP design.

Material

This research focuses on redesigning GP with an alternative material. This alternative should be an improvement upon the current materials used. From the current situation and the context, requirements are formed to identify potential alternative materials. Through research, different sustainable materials are considered. Choosing the material most suitable for GP design is done according to the requirements.

Tinkering

Material engagement, physical encounters with a material, practical enquiries, learning by doing, thinking and reflecting, understanding material, process and form and the relationship between them, all fall under the action called 'tinkering' (Karana et al., 2015). Through tinkering, designers develop an intuitive understanding of a material's behaviour under different conditions and manufacturing processes, eventually becoming "a master of a given material" (Karana et al., 2015).

Technical Characterisation

Technical characteristics describe the mechanical properties of a material and its suitability for specific applications. Mechanical testing provides data regarding the mechanical properties of a material. Pavement experiences various loading conditions, but for the purpose of this study, these conditions are simplified and represented as a compressive force. Unconfined compressive testing was conducted to understand the compressive behaviour of different material samples. The goal of this testing is to determine material properties that enable a feasible final design.

Experiential Characterisation

Human-centered material characteristics, referred to as experiential characteristics, define how a material is perceived and experienced by users (Karana et al., 2015). To assess the user experience of the material, interviews were conducted with key stakeholders. Understanding the experiential characteristics of the material contributes to designing a user experience that aligns with both the material's properties and its application as Grid Pavement.

Final Concept

The research is concluded into a sustainably materialised GP design. A user experience vision fitting both the experiential character of the material and the application guides the design of the final concept. The mechanical properties obtained through technical characterisation serve as input parameters for Finite Element Analyses (FEA) simulations, ensuring that the final design meets structural and performance requirements. Due to the scale of the final concept, scale models and material samples aim to express the product aspects and material qualities without producing a full scale model from the sustainable material.

3 context

Which stakeholders are involved during the lifetime of GP?

- What is the role of each stakeholder?
- How much power does a stakeholder have?

What design requirements are present for GP?
What design requirements are present for sustainable materials?
What opportunities arise from the context?

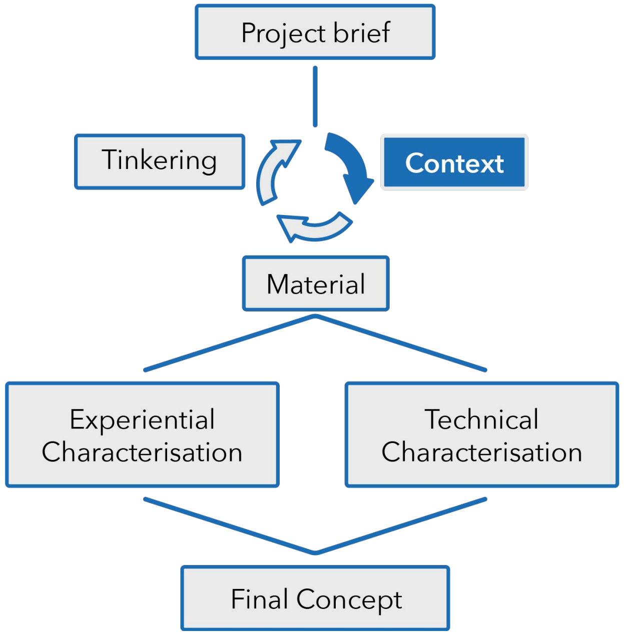


Figure 7: Context section in the project structure

This chapter seeks to form an understanding of the context of Grid Pavement and sustainable materialisation. The goal of understanding the context is to form criteria and find opportunities for designing Grid Pavement from a sustainable material. Additionally, by understanding the role of different stakeholders, the stakeholders relevant for the experiential analysis can be identified.

To reach this understanding of the context, interviews with stakeholders are described in section 4.1, and an analysis of the current GP market is done in section 4.2.

3.1 Stakeholder Interviews

To understand the context, interviews were conducted, focussing on Grid Pavement and sustainable materials.

3.1.1 Method

Participants

Important stakeholders regarding GP and sustainable materialisation were selected as participants through an orientating interview. Two interviews were conducted with two stakeholders per interview (Table 1). Each interview was without structure to increase the natural flow of the interviews. Questions regarding materialisation, design of the public and Grid Pavement were the focus. Two participants were employed by a Dutch municipality and two by an architecture and construction company. Participants were recruited through e-mail contact.

Stakeholder nr.	Stakeholder type	Function	Duo
1	Municipality	Policy maker Climate Adaptation	1
2	Municipality	Civil Technical Advisor	1
3	Architecture and construction company	Architect	2
4	Architecture and construction company	Project planner	2

Table 1: Stakeholder interviews participants

Materials

An iPad was used to record audio during the interviews. The audio was transcribed using Turboscribe.ai (https://turboscribe.ai). This provided a fairly precise transcription, but occasionally text had to be altered using the original audio. Relevant findings were manually selected from the transcriptions and translated from Dutch to English. ChatGPT (https://chatgpt.com) was used to summarize these conclusions in a well-organized bullet point list.

Procedure

All participants were informed in the recruitment e-mail that the study regards designing GP with sustainable materials. Each interview was scheduled to take 60 minutes, at the stakeholder's employment location. Upon settling in an interview appropriate space, an informed consent form (Appendix A) was signed by participants.

To identify requirements for Grid Pavement design, a list of requirements and wishes was made.

3.1.2 Results

Transcription of the full interviews can be found in the Supplementary material. The relevant findings for interviews 1 and 2 are summarised in Appendix B.

3.1.3 Discussion

Interview 1

Regulations and Municipal guidelines

The municipality requires Grid Pavement to be compatible with street-laying machines, with regulations on the horizon to ensure workplace safety for roadbuilders. Street-laying machines efficiently place a bundle of pavers using specialized clamps (Figure 8 and 9) (Not Just Bikes, 2025; jef0611, 2016). Machine paving reduces costs, time, and physical strain on roadbuilders (Nemaco, n.d.; Stakeholder interview 1). GP should be efficiently placed on palettes for machine distribution, while GP modules have to be graspable by clamps.

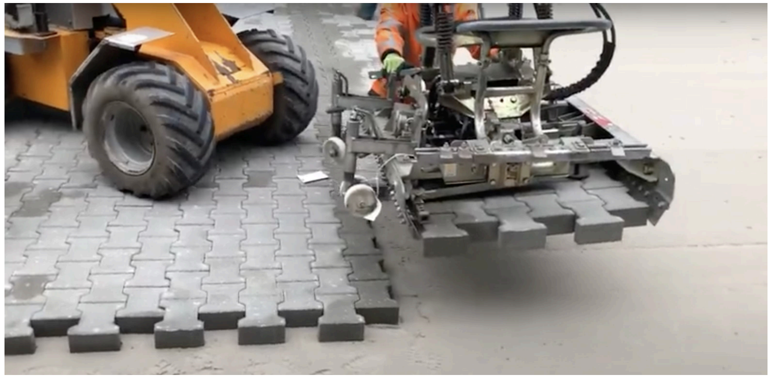


Figure 8: Paving clamp grabbing multiple pavers in a pattern (Not Just Bikes, 2025)

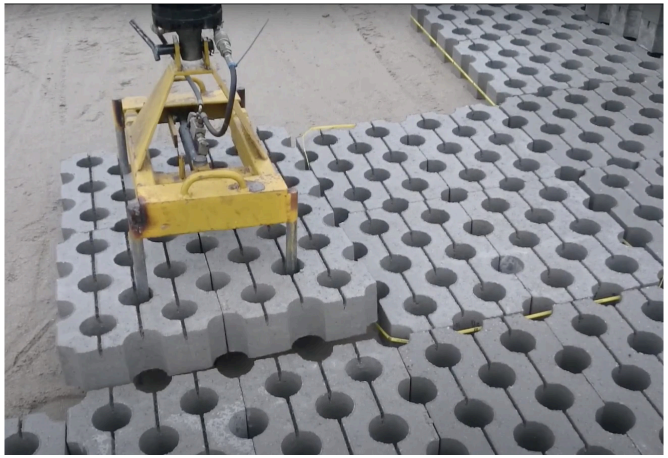


Figure 9: A Grid Pavement clamp, utilizing the open cells as points for grabbing (jef0611, 2016)

The LIOR of this municipality can be found online but will not be cited for anonymity reasons. The LIOR shows that the regulations of this municipality for GP are:

- Material: Baked or concrete (no plastic)
- Installation possible with machinery
- Minimally 30% open space

A material from the options currently on the market is specified: Baked or concrete. A sustainable material might be included into the guidelines if it were available. It confirms the previously discussed regulation of machine-paving. The TAWWA Grids feature 50% open space including and roughly 16% excluding the water gutters at the bottom (Figure 10). Whether the open surface would be viewed by the municipality as 50%, 16% or somewhere in between is unclear. However, since the load bearing surface provides 50% open space, it is viable for current TAWWA Grids to meet the municipality's 30% open space requirement.

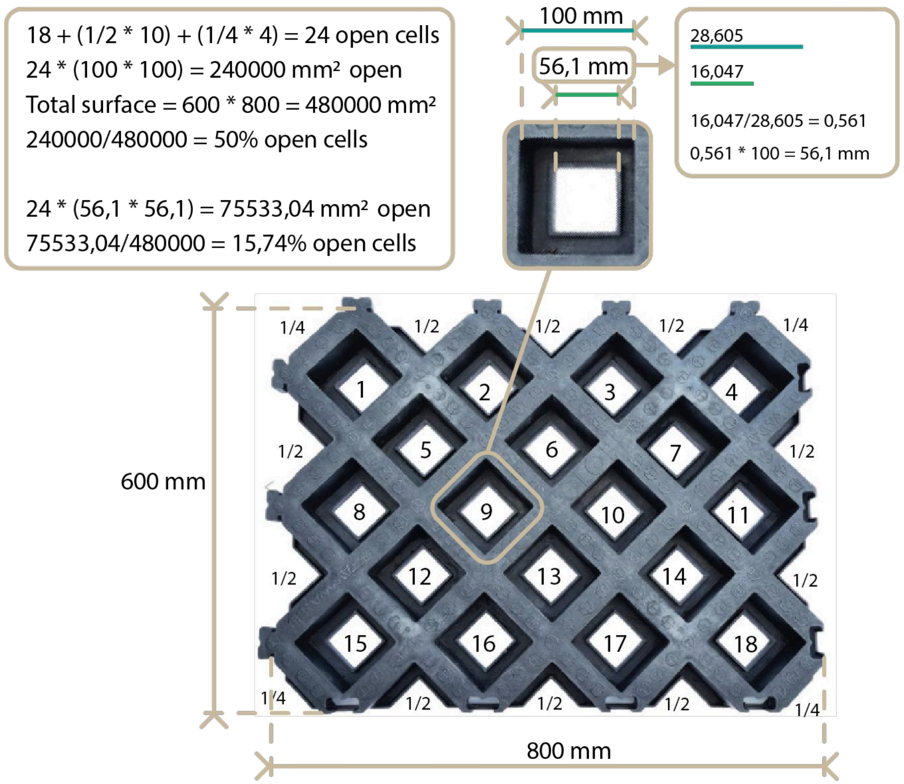


Figure 10: Open surface calculations on current TAWWA Grids

The municipality has mapped certain areas with excessive impervious surfaces fit for replacement with vegetation providing measures like GP. This can speed up the effective implementation of GP in a municipality.

Requirements regarding water and heat management and green space are set by the municipality. These rules will become clearer and stricter as climate-adaptive urban planning becomes more relevant.

Municipalities can choose to implement solely pavement of a certain shade. Colours for pavement commonly include shades of blue, red, purple, black, grey, yellow and brown (MBI De Steenmeesters, 2023). A material with pigmentation potential can improve the market acceptance of redesigned GP.

Standardization and adoption of GP

Urban planning guidelines to standardize vegetation in urban areas like the 3-30-300 rules are used in urban planning. This level of standardization could make GP a more common practice. A standard for GP like: "30% of the parking spaces should be made from GP." could ensure a systemic inclusion of GP in urban planning.

If (Grid) pavement meets the municipality's needs, it is likely to be implemented municipality-wide as municipality favors consistency in pavement products. Sustainable and durable GP could lead to widespread implementation.

Sustainable knowledge of municipalities

In the interview recruitment e-mail as well as the interview, 'bio-based' was the most used term for sustainable materials. Bio-based refers specifically to materials made from renewable sources. However, due to current products in various industries being labelled e.g., 'eco', 'bio', 'biodegradable', confusion is likely to occur.

The municipality perceiving recycled plastics as unsustainable shows their sustainable knowledge. They are aware of certain labels and marketing strategies being 'greenwashing', where the sustainability of products or materials is exaggerated or framed to include only the positive aspects.

Sourcing renewable materials locally would offer the opportunity of combining local agriculture and manufacturing. This would increase the sustainable appeal for Municipalities and potentially for users as well.

Municipalities have sufficient knowledge of sustainable products to consider the entire life cycle. This means no phase of the life cycle of a product should be neglected in its sustainable development. It also shows the added value of providing a Life Cycle Assessment (LCA) with the presentation of a sustainable product or material. Additionally, water authorities will not be considered in further research as materialisation is not important to them.

Market acceptance of CoRncrete GP

Municipalities had negative past experiences with Grid Pavement failing to grow healthy vegetation due to insufficient knowledge about sub-soils and installation protocols. To address this, TAWWA Grids incorporated gutters to improve water retention, enhancing vegetation growth. Additionally, Tonn sells sub-soils that support vegetation growth.

Grid Pavement is best suited for large-scale projects in newly built areas or major redevelopments, requiring high production volumes. Current TAWWA Grids are injection moulded, a widely used manufacturing process for plastic products, known to be cheap and scalable. Producing 10,000 parts takes about 3 weeks, or 44 seconds per part under optimal conditions (A.C.E., 2023).

Grid Pavement (GP) is one of several climate-adaptive measures in urban planning and should be implemented only when it is the most effective solution for a given space. Implementation of GP without careful analysis of the context of use can result in poor vegetation growth, disappointing residents and creating a bad image for GP.

Importance of the municipality as a stakeholder

Municipal management oversees maintenance of public spaces, including pavement and vegetation. The vegetation of GP needs to grow for it to be considered aesthetically pleasing and a successful climate adaptive technology. Municipalities prioritize orderly greenery and clean pavement, requiring regular maintenance. Grid Pavement poses a challenge for maintenance due to the combination of pavement and vegetation.

In new developments, costs of constructing the public space are borne by developers. When only the public space is redeveloped, the municipality bears the costs. Both developers and municipalities value sustainable measures, but costs remain the decisive factor.

Municipalities can initiate 'Pilot projects' with a product. This means products who are not completely certified are offered the opportunity to be implemented in a project. Pilots can provide traction for innovations, potentially leading to new investments and sales. Through a Pilot project, long-term data can be generated for CoRncrete GP, accepting that the outcome can also be negative. Actively generating data is currently also new to municipalities, but no reason could be identified that makes data generation impossible.

Municipalities understand the added value of renewable materials. Hemp is known to absorb harmful substances like PFAS from the soil (UHasselt, n.d.), while Japanese Knotweed is an invasive plan species, causing damage to the public space and biodiversity (Why Knot Design, n.d.). The municipality sees potential in using a renewable source with positive side effects like hemp and Japanese Knotweed.

Interview 2

Roles and responsibilities in design and construction

Architects focus on the construction of aesthetically pleasing, useful buildings. Landscape Architects focus on the design of the public space. Different regulations apply for buildings and the public space.

External experts consult the architect, making the final changes to the design. The consult is an advice, with the power remaining largely in the hands of the architect. Through concessions the architect balances costs, aesthetics, and practicality.

(Landscape) architects include materials into their envisioned designs. To understand the power of an architect, stakeholder 3 gave the example of an overhanging canopy (Figure 11). In an architect decides to include such a feature in their sketches, the constructional expert will tell them in the preliminary design phase that there are multiple options. The cheapest is to put supporting beams underneath it. However, if the overhanging effect is crucial for the aesthetic of the design, the architect has the power to make it happen. Since such a feature would be expensive, other features might be made cheaper. This way the architect balances between the advice of the experts and the aesthetics and use of the building. An architect that is set on using Grid Pavement, CoRncrete or CoRncrete Grid Pavement, will have the power to make this happen. Construction teams require different information than architects regarding GP. Integrating stakeholders from construction would be crucial in designing the installation information.

Figure 11: A building with a 16 meter overhanging canopy (Wind, 2024)

Government regulations

Local and national government provide visions and plans for areas. An area vision (Dutch = gebiedsvisie) outlines guidelines for development, integrating aspects like housing, nature, recreation, sustainable energy, and traffic (Gemeente Opmeer, 2023; Gemeente Delft, 2021). Local residents, businesses, and institutions contribute through collaborative sessions (Gemeente Delft, 2020; Gemeente Opmeer, 2023). A land-use plan (Dutch = bestemmingsplan) then details how each lot should be developed to implement the area vision, specifying permitted construction, usage (e.g., residential, commercial, traffic), and additional requirements (Gemeente Delft, 2020; Gemeente Den Haag, 2024; Gemeente Rotterdam, n.d.). Every municipality has designated land-use plans, which are accessible on the national website Regels op de Kaart (Gemeente Den Haag, 2024; Gemeente Rotterdam, n.d.). Both the area vision and land-use plan undergo a review process where responses and appeals by residents, businesses, and institutions can be submitted before finalization (Gemeente Opmeer, 2023) (Gemeente Delft, 2020) (Gemeente Delft, 2021). Image quality plans (Dutch = beeldkwaliteitsplan) are sometimes included for certain areas of a municipality, imposing requirements such as no use of bricks, add a height element, use natural materials, for example. These visions and plans show the power of the municipality over designs of the public space. Alternatively, they also give an idea of the sort of requirements the municipality can impose, introducing additional design requirements for implementation of GP.

Materials used in new buildings should have a low environmental impact, in NL calculated by the MPG or Environmental Performance Buildings (Rijksdienst voor Ondernemend Nederland, 2024b). The environmental impact of a material is documented in the NMD or National Environment Database (Rijksdienst voor Ondernemend Nederland, 2024b). With this impact an LCA is done, which gives an MPG value for a building (Rijksdienst voor Ondernemend Nederland, 2024b). This value should be lower than 1 for office buildings above 100 m2 and 0,8 for residential buildings (Rijksdienst voor Ondernemend Nederland, 2024b).

Buildings should also have an Almost Zero Energy Usage, or BENG in Dutch (Rijksdienst voor Ondernemend Nederland, 2024a). The MPG affects the BENG and vice versa. For example, while thicker insulation or solar cells improve energy efficiency, they also worsen the MPG (Rijksdienst voor Ondernemend Nederland, 2024b).

CoRncrete GP could contribute positively to both the BENG and MPG through sustainable materialisation and lowered energy use for cooling the building. However, current MPG regulations only include construction parts as confirmed in e-mail contact with the responsible government body (Appendix C). The e-mail specifically states that sustainable materialisation in pavement does not affect MPG calculations but is desirable from a sustainable point of view.

The Bouwbesluit is an elaborate document of regulations including those relevant for pavement materials.

Market introduction and certification

Certifying CoRncrete GP's technical capacities allows for wide-spread adoption by landscape architects. However, this is expensive and takes a long time. Additionally, with every improved version of a product, the certification process needs to restart. This company has its own award for novel materials, where the best novel material can win a pilot project. Alternatively, by providing long-term data, the company might take some risk and implement CoRncrete GP in a project. The advantage for Grid Pavement is that it is not featured within a building, making fire resistance, among other strict regulations, irrelevant.

The company has their own database of innovative, sustainable materials in the form of an app. Alternatively, online databases such as Ubuntoo (ubuntoo.com), Material District (materialdistrict.com) and Bio Based Press (biobasedpress.eu) gather knowledge about sustainable materials for designers to use.

Implementation and market adoption

In contrast to this company, design and construction are generally handled by different parties. The interview showed that as more parties become involved in a design and construction process, communication and like-mindedness become increasingly important.

Scaling a novel material as a startup is difficult due to the lack of funding and industry knowledge. Introducing CoRncrete GP to the market requires visiting fairs, doing online research, attending sales meetings and competing in design challenges. A well-known fair in The Netherlands is Material District in Utrecht, where numerous companies and speakers attend a 3-day event to share knowledge and showcase novel materials (Van Der Wijk, 2024).

Sustainable materials in construction

According to stakeholder 4, a product containing 80% bio-based materials qualifies to be labelled 'Bio-based'. Stakeholder 3 stated that this can lead to confusion and greenwashing by adding 20% very harmful materials while labelling a product bio-based. NEN, the institute for Dutch Norms defines bio-based as "materials partly or fully made from biomass" (NEN, n.d.), leaving room for discussion and addition of harmful materials. This makes bio-based labelling confusing and leaves potential for greenwashing in material development.

Through a matrix mapping system, the company decides on different sustainable design features. For every function multiple sustianable alternatives are therefore sought after. According to interview 2, construction companies and architects in general are actively looking for sustainable materialisation, while municipalities care less.

According to interview 2, comparing concrete to CoRncrete pavement should be done over its useful lifetime as concrete emissions are diminished due to its longevity. Using application fitting concrete mixtures (Balogh, 2023) and proper maintenance, concrete is believed to have a useful lifetime of up to 100 years (Arkin, 2023). A long lifetime requires less new building materials and spreads the environmental footprint, reducing the emissions in relation to the full lifetime of concrete products (PCA, 2024).

According to interview 2, wood is rated worse than concrete in the MPG due to false assumptions about post-use emissions. This would mean the renewable fraction of CoRncrete is also rated worse than expected, potentially resulting in CoRncrete having a worse MPG than concrete.

3.1.4 Conclusion

Requirements and wishes

The findings of the interviews can be translated to requirements and wishes to ensure the design is context relevant. These are mentioned in section 4.3.

Opportunities

As cities grow and environmental concerns rise, water and heat management regulations are becoming increasingly relevant. This shift makes Grid Pavement (GP) increasingly relevant, offering a sustainable solution for urban planners.

Integrating pigmentation can create a variety of aesthetic options that can seamlessly blend into different architectural styles. Urban planning principles like the 3-30-300 rule could make GP a standard solution in urban design, creating a sustainable city with integrated vegetation.

Full scale validation of the redesign is key to widespread adoption. Certification is the highest grade of validation but requires large amounts of money and is time-intensive. In contrast, pilot projects with municipalities and construction companies can provide valuable long-term performance data, helping to demonstrate the reliability of GP. This data could persuade municipalities and architects to implement the redesigned GP in the near future, without the need for official certification. Additionally, since GP is mainly used in parking lots and public spaces, applications with lower risks, companies may be more inclined to experiment with the redesign even without certification.

Stakeholder engagement is crucial. The benefits of redesigned GP should be clearly communicated to municipalities, architects, and developers. The conducted stakeholder interviews revealed a strong interest in sustainable pavement materials. Additionally, if pavement materials are eventually included in the MPG (Milieu Prestatie Gebouwen) score, the demand for sustainable pavement solutions could increase.

Being featured in material databases, such as the app of the interviewed company or online platforms, and to participate in design competitions like their award program, could create more awareness of the redesign. Trade fairs, a strong online presence, and direct sales meetings will also help establish the redesigned GP in the market.

Collaboration with (landscape) architects and construction companies with sustainable goals, and leaders in the pavement industry can accelerate implementation and drive widespread acceptance. By taking these steps, the redesign can position itself as a practical, sustainable, and innovative solution for the future of urban infrastructure.

Key stakeholders

Municipalities set the material requirements for GP and have the authority to include CoRncrete in these standards. Meeting municipal requirements with a GP product can lead to large-scale implementation, as municipalities prefer consistency in pavement materials.

Certain areas with excessive impervious surfaces have already been mapped, allowing for quick replacement with GP. Interviews confirmed that municipalities have significant power to introduce new materials through pilot projects.

Additionally, municipalities enforce guidelines that may impose extra design requirements for GP implementation. They also have the authority to include specific materialization requirements and recognize the added value of renewable materials.

Architects make the final design decisions, though they are advised by external experts. Both architects and landscape architects have the power to incorporate sustainable materials beyond regulations and understand the additional costs of sustainable design. A determined architect can ensure the implementation of CoRncrete GP by making concessions on costs, aesthetics, or practicality in other aspects of the design. Architecture and construction companies actively seek sustainable alternatives, using databases to map and select the most relevant materials for each project, including GP.

Originally, it was assumed that only one group of stakeholders would be pursued in the experiential research. However, due to the different types of power owned by the municipality and the architects, both will be included in the experiential research. To ease the recruiting process, the same stakeholders will be recruited.

Limitations

Since no physical TAWWA Grid was available during the project, its dimensions had to be estimated based on assumptions.

Interview 2 included an architect rather than a landscape architect, and the stakeholders focused on office buildings rather than residential spaces. As a result, the gathered insights may be more relevant to designing the limited public space of office buildings.

The participants from the municipality and construction company had extensive knowledge of and affinity with sustainability, which may have led to a more favorable perception of GP and sustainable materialisation than the average of each stakeholder type.

Due to the complexity of the Bouwbesluit, its requirements were not considered. Instead, requirements for GP were mainly based on interviews, which reflect subjective information from four stakeholders rather than facts from a government document.

Future research

Future research should establish an installation guide for the redesign, including machine-laying techniques to ensure a safe workplace for roadbuilders and sub-soil considerations to support vegetational growth. Construction-focused companies should be involved, as they are responsible for the proper use and installation of GP.

GP is one of the climate-adaptive measures available in urban planning. Future research should identify when and where GP is the most cost- and climate-effective solution. Future research should explore GP maintenance in collaboration with municipal managers.

To draw more nuanced conclusions on GP and sustainable materialization, future research should interview municipalities of various sizes and locations. Additionally, landscape architects specializing in residential and business premises should be included to gain insights into GP implementation in different urban environments.

Further studies should explore how GP is best introduced to the market and how vegetation growth in GP can be optimized. An LCA could help persuade municipalities to use GP. Future research should use values from the NMD while considering the long lifespan of concrete for a realistic comparison.

Since long-term data collection is time-intensive, research on GP should immediately start collecting data. Future iterations of the redesign can be included later, but the priority should be a substantial dataset over an extended period. Additionally, industry experts with experience in the Bouwbesluit should be consulted to list relevant requirements for developing sustainable GP.

3.1.5 Reflection

Interview 2 gave me a lot of information about the municipality even though it was an interview with an architecture and construction company. It might be difficult for stakeholders involved in complex processes to pinpoint what their role exactly is. The interviews taught me the importance of asking stakeholder 1 (e.g., the company) for the role of stakeholder 2 (e.g., the municipality) within a process as it is easier to talk about others. Additionally, this method allows researchers to cross-check what stakeholders say about themselves, increasing the accuracy of the research.

3.2 State of the Art (SoA)

Currently, different types of GP are available on the market, made of plastic or concrete. Looking at the current market shows important context factors and design requirements.

3.2.1 Method

The current Grid Pavement market was analysed for contextual information.

Subjects

Pictures and technical data of GP were found on the internet. Additional pictures of GP that was encountered during this study is used.

Materials

The internet was used to find subjects, Microsoft PowerPoint was used to structure the findings, while Adobe Illustrator helped visualise the findings.

Procedure

English search terms and their Dutch translation were used to find subjects on the internet. The terms used are “Grid Pavement”, “Grasdallen”, “Grastegel” individually and in combination with “Plastic”, “Concrete” and “Beton”.

3.2.2 Results

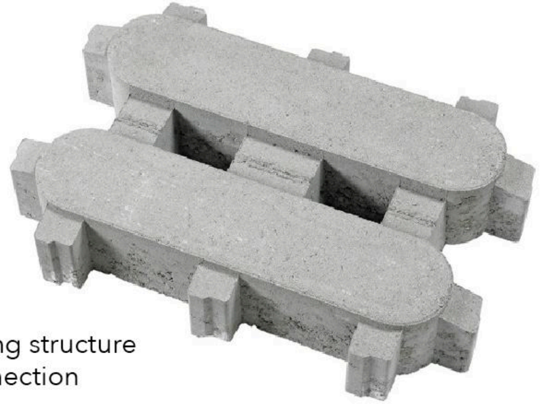
(ClimateScan, n.d.)

(123Sierbestrating, 2024)

'Hidden' connection
within element

Rounded shape looks
more playful

'Hidden' connection
between elements



Alternating structure
connection

(Marlux, n.d.-c)

Compatible with regular
bricks

Different size 'hidden'
spacers create fading
effect

Fading connects plants
to infrastructure

Compatible different shapes

Typical brick patter

(Marlux, n.d.-a)

Long lines create
structure

(Swaans Infra, n.d.)

Functional space
between vegetation

More lines increase expected grip

A lot of visible material makes it look strong, trustworthy

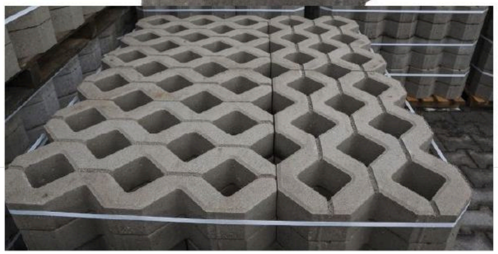
(Milan, n.d.)

Zig-zag pattern over full width of parking spot

Distracting lines, not contributing to aesthetics

Spacers with alternating placement on the left or right

Square cells

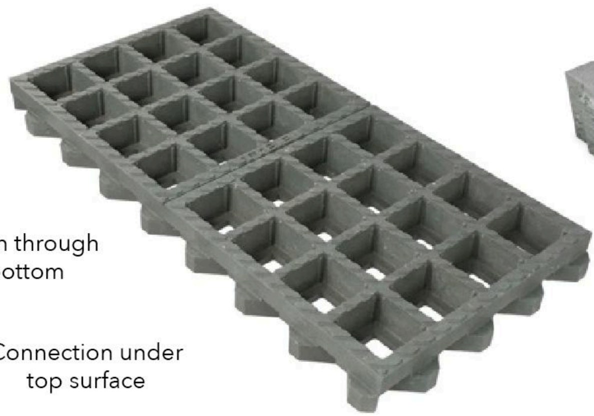


Bigger elements. Geometrical shapes

(Bestrating.nl, n.d.)

Plastic

Flat spacers under top surface. Different lines connected through ribs under the top surface



Connection through fitting bottom

Connection under top surface

(Azalp.nl, n.d.)

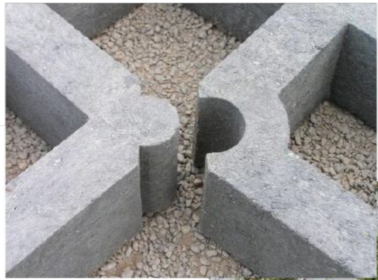
Bigger elements. Geometrical shapes. Rectangular cells

600 x 400 x 120 mm

Concrete

(MBI De Steenmeesters, n.d.)

Connection through
'puzzle piece' shape



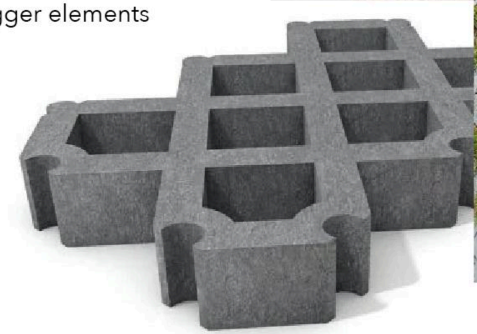
Requires simple mould

Geometrical shapes

Square cells

Plastic

Bigger elements



(Kunststof Forte BV, 2024)

Connection at top
surface visible

No connection or spacers

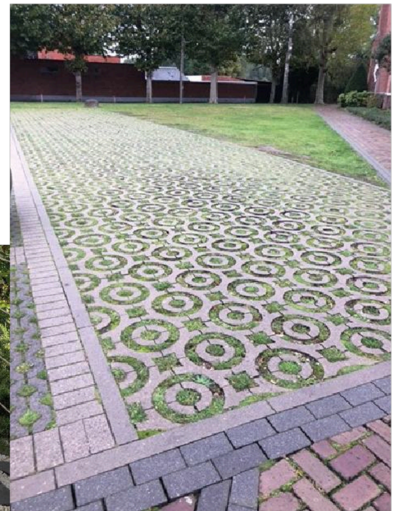
'Invisible' connection

Spacers with alternating two or
one vertical strip

375 x 375 x 70 mm

Concrete

Pattern of hexagonal
blocks, geometrical
internal openings



(Marlux, n.d.-b)

(Steenvoordeel, 2024)

Pattern of diagonal lines with internal
openings, more expressive

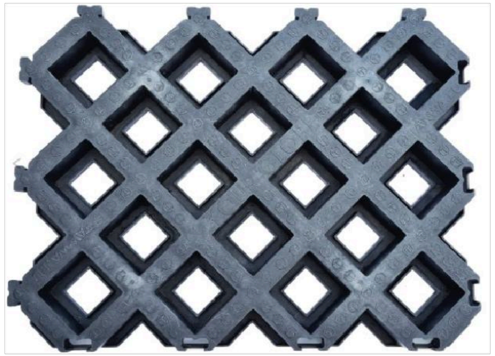
Smaller
elements

Novel shapes

Interlocking connection

600 x 800 x 80 mm

Plastic

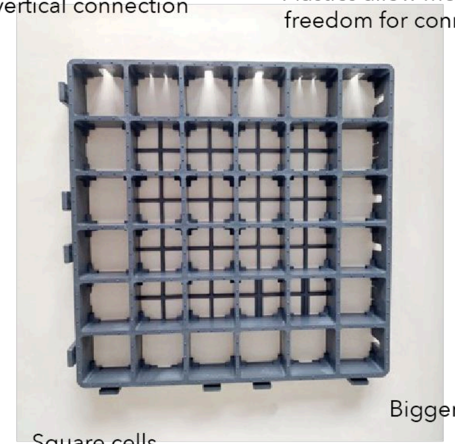


(Tonn, 2023)

Geometrical shapes

Assemble through vertical connection

Plastics allow more form freedom for connection



Square cells

Bigger elements

(Gridforce, 2025)

Zig-zag pattern

Distracting lines

More lines increase expected grip

(Jos Janssens & Zonen, 2023)

Looks like bricks with added grass

Typical brick pattern

Compatible with regular bricks

300 x 100 x 100 mm

'Hidden' ribs connect within element

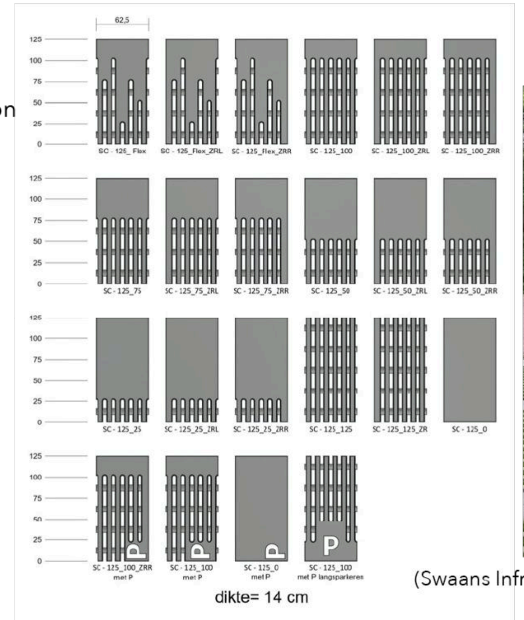
'Hidden' pointed spacers under top surface

300 x 300 x 100 mm

(Marlux, n.d.-a)

Different elements for beginning and end

No connection or spacers



(Swaans Infra, n.d.)

Different elements for function and aesthetics available

Ribs between grass are smaller than grass lines.

Rectangular cells

Geometrical shapes

Bigger elements

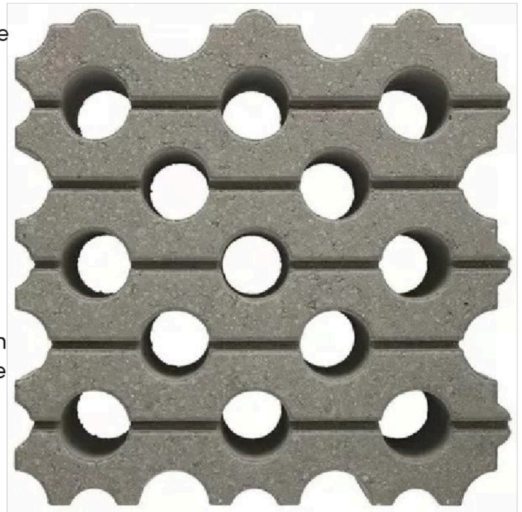
Lateral lines of grass and longitudinal lines in-between create long lines in the landscape

Connection at top surface visible

Concrete

600 x 600 x 160 mm

Connection through 'puzzle piece' shape



(Nubuiten.nl, n.d.)

Circular cells

Round patch of vegetation looks like weeds

Compatible with brick pavement

3.2.3 Conclusion

Connection

Different modules can be connected in different ways. Plastic products are able to include interlocking mechanisms due to the form-freedom of injection moulding. Concrete GP modules feature puzzle-piece connections, where the modules are laid against each other, while a half-circle, or vertical lines keep the modules from moving apart. Some connections are merely flat spacers between modules, where the material's surface roughness and weight minimise pavement movement.

Connections between modules can be visible at the top surface or be 'hidden' under the topsoil. 'Hidden' connections are placed lower than the functional surface, providing more space for vegetation while providing a connection and structural improvements. More visible gives the pavement a trustworthy look, while 'hidden' material improves the nature aspect of the design.

Modules

GP elements are either larger, comparable to TAWWA Grids or smaller, comparable to pavement bricks. Elements can get as big as 600 by 600 mm with a thickness of 160 mm (Nubuiten.nl, n.d.) and as small as 300 by 100 mm with a thickness of 100 mm (Marlux, n.d.-a). Bigger elements might be more suitable for machine-laying, while small elements might be more suitable for manual work. However, the smaller elements can, like bricks, be prepared in the desired pattern to be machine-laid.

More visible lines create a more grippy texture compared to a solid slab. Increasing the amount of visible lines could improve the perception of the redesigned GP as trustworthy. Existing GP use zig-zag patterns or grooves.

Parking lot aesthetics

Using GP for parking lots requires walking lanes between the parking spaces to provide accessibility to handicapped, elderly and people walking on heels. Additionally, the wheels can be placed on these lines, reducing the stress on the vegetation, likely resulting in healthier vegetation. Some GP elements include this into the design while other elements allow for connection to bricks that can form fully paved connections between GP parking spots.

Grid Pavement layout

GP can have geometrical open cells or more expressive open cells. Geometrical shapes give the elements an industrial, more serious look. Expressive open cells create an elegantly paved area with interesting lines and patterns.

Long connected open cells create more integrated vegetation. Additionally, the long sight lines create a calmer grid pavement layout as it adds structure to the public space. Shorter lines break up the vegetation and pavement, creating a less integrated look.

Varying size of open cells can create a fading effect between pavement and vegetation. This fading effect removes the hard borders between pavement and vegetation, creating a harmonious collaboration to create a functional and sustainable urban space.

Sustainability

Current Grid Pavement is made out of Plastic or Concrete. Reversible connections allow for repair and reuse of Grid Pavement surfaces, extending the lifetime of the public space and Grid Pavement

3.3 Conclusion

The findings of this chapter are concluded in requirements and wishes that guide the design to be context-relevant.

Stakeholders

Requirements | Wishes

Minimum of 30% of the Grid Pavement surface should be open cell
Terms like bio-based, biodegradable, biological, eco, etc. should be avoided in material categorisation
Redesigned Grid Pavement should be liftable with machine clamps
The length of the redesign should be 50 to 100 mm, 150 to 200 mm, 350 to 400 mm or 750 to 800 mm to optimise palette layout
The width of the redesign should be 50 to 100 mm, 150 to 200 mm, 250 to 300 mm or 550 to 600 mm to optimise palette layout
The redesign material should be comprised of abundant materials
The redesign material should be manufactured using processes capable of producing numerous and/or large-volume products
The redesign material could be able to incorporate different colours as a material appearance
The costs of the redesign material should be as low as possible
The weight of the redesigned Grid Pavement should be as low as possible
The redesign material could include (renewable) materials with beneficial side effects

GP State of the Art

Requirements | Wishes

The redesign should prioritize fewer, larger visible surfaces over many smaller ones
A parking lot featuring the redesigned Grid Pavement should result in long lines of pavement and vegetation
The thickness of the redesign should be between 60 and 160 mm
The redesign should look like smaller elements while being constructed as one large element
The open cells should form a repetitive pattern when multiple elements are connected
Open cells should be rectangular
The redesign should be compatible with regular Dutch brick pavement
Invisible spacers can help create long lines of vegetation while providing structural strength
Visible spacers can help create reliable surfaces while providing structural strength
Different sizes of open cells could be included to create a fading effect
Increased number of visible lines could improve the perceived grip of the redesign

4 materials

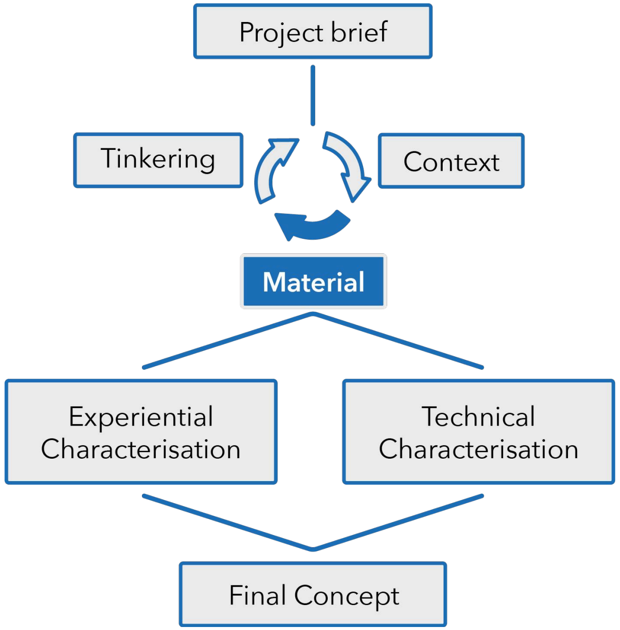


Figure 12: Material section in the project structure

What is the best sustainable alternative material for grid pavement?

- *How sustainable are the current materials used in grid pavement?*
- *What sustainable requirements are present for grid pavement?*
- *What challenges does desirable and feasible implementation of this alternative material pose?*

The goal of this chapter is to understand the criteria for sustainable development to find a sustainable alternative material for Grid Pavement (GP).

First the environmental impact of the current materials used for GP are described. From this, requirements for a sustainable alternative material are explained. Consequently, materials considered for this research are explained, followed by the material of focus for this research.

4.1 Current Materials

Current GP is made from either concrete or plastic (Shakrani et al., 2018; Scholz & Grabowiecki, 2007; Palla et al., 2014). These materials are used due to their numerous benefits, however, their environmental impacts bring challenges for a sustainable future.

4.1.1 Concrete

Concrete is the most used man-made material globally (Miller & Moore, 2020; Monteiro et al., 2017), being highly sought after due to its cost-effectiveness and ease of manufacturing (Miller et al., 2016). Concrete consists of cement, water, granular rocks (aggregates), and application-relevant additives (Miller et al., 2016; Monteiro et al., 2017; Miller & Moore, 2020).

Concrete is responsible for 8% of Greenhouse Gas (GHG) emissions created by humans (Miller et al., 2016). Cement, reacting with water to form the binder of the aggregates, makes up 90-95% of concrete's GHG emissions (Miller et al., 2016). About 95% of cement is clinker, where two aspects are responsible for roughly 90% of the clinker's emissions (Müller & Harnisch, 2008). Firstly, calcium carbonate ($CaCO_3$) reacts and produces calcium oxide (CaO) and carbon dioxide (CO_2) (Monteiro et al., 2017; Miller et al., 2016; Müller & Harnisch, 2008). Secondly, this reaction requires temperatures up to 1450 °C, requiring large energy inputs from fuel combustion (Monteiro et al., 2017; Miller et al., 2016; Müller & Harnisch, 2008). Concrete manufacturing produces roughly 8% of the anthropogenic GHG emissions (Monteiro et al., 2017; Müller & Harnisch, 2008). Additionally, concrete's freshwater demand stresses the already scarce natural resource (Arrigoni et al., 2022). Due to its desirability and the nature of its production, concrete is incredibly difficult to decarbonize, with material replacement being a relevant mitigation strategy (Davis et al., 2018).

4.1.2 Plastics

Plastics are molecules linked together in chains to form polymers (Plastics Europe, 2023). Molecule sources include sugar, corn, coal, and crude oil (Plastics Europe, 2023; Andrady & Neal, 2009) but plastic is derived mainly from non-renewable fossil fuels (Hopewell et al., 2009; Andrady & Neal, 2009; Geyer et al., 2017). Plastics are versatile, cost-effective, lightweight and durable (Hopewell et al., 2009; Andrady & Neal, 2009; Plastics Europe, 2023).

However, plastic production contributes to air and water pollution through the release of harmful chemicals, induce climate change due to its carbon footprint, and deplete non-renewable fossil fuel reserves (Saleem et al., 2023; Hopewell et al., 2009; Lebreton & Andrady, 2019). In 2017 was estimated that roughly 9% of global plastic waste has been recycled, 12% incinerated, while 79% has accumulated in natural ecosystems (Geyer et al., 2017). During use and after disposal in landfills, plastic degrades through exposure to e.g., UV or friction, into small particles carrying the harmful chemicals used in plastics (Andrady & Neal, 2009; TNO, 2001; Horton, 2021; Walker & Fequet, 2023; Geyer et al., 2017; Alsabri et al., 2021). These particles harm nature, animals and humans through soil, food, water and air (TNO, 2001; Geyer et al., 2017; Borrelle et al., 2020; Alsabri et al., 2021; Borrelle et al., 2020). With GP being in direct contact with soil and water, plastics in GP could easily affect human and animal health.

Recycling plastic waste has the potential to mitigate its environmental impact (Saleem et al., 2023; Geyer et al., 2017). However, this benefit is limited by the fact that a substantial portion of plastic waste is not actually recycled (Geyer et al., 2017). Additionally, "recycling delays rather than avoids, final disposal" (Geyer et al., 2017) and the impacts of plastic particles are not diminished by using recycled plastics.

4.2 Requirements

The goal of this research is to find a sustainable material replacement for current GP. Sustainable, manufacturing, and mechanical requirements and wishes help distinguish relevant for a material replacement for GP.

4.2.1 Sustainability

Sustainable development strategies (Figure 13) and the harmful character of concrete and plastic indicate sustainable requirements for material development. Sustainable design strategies allow for systematic and structured improved sustainability across the full lifetime of a product (Mouëllic et al., 2023).

Dematerialisation

The weight of the redesign should be minimised to reduce the energy consumption of transportation and the strain on road workers handling the GP (Mouëllic et al., 2023). The redesign should be durable to withstand transportation with minimal protective packaging.

Next-best material selection

The first step of manufacturing is sourcing materials. Renewable raw materials like wood can be replenished through biological processes that capture carbon while producing biomass (Stora Enso, n.d.). Manufacturing with renewable materials is virtually infinitely maintainable in contrast finite resources like fossil-fuels (Stora Enso, n.d.). As emphasised by the interviewed municipality, sourcing renewable materials locally is prioritised. This reduces the financial and ecological impact of transport and simultaneously boosts the local agricultural sector.

Using recycled materials and the material being recyclable reduces extraction of virgin materials and waste generation (US EPA, 2025).

A lightweight material reduces the energy consumption of transportation as well as reduce the strain on road workers handling the GP. Ideally the alternative material has a lower density than concrete.

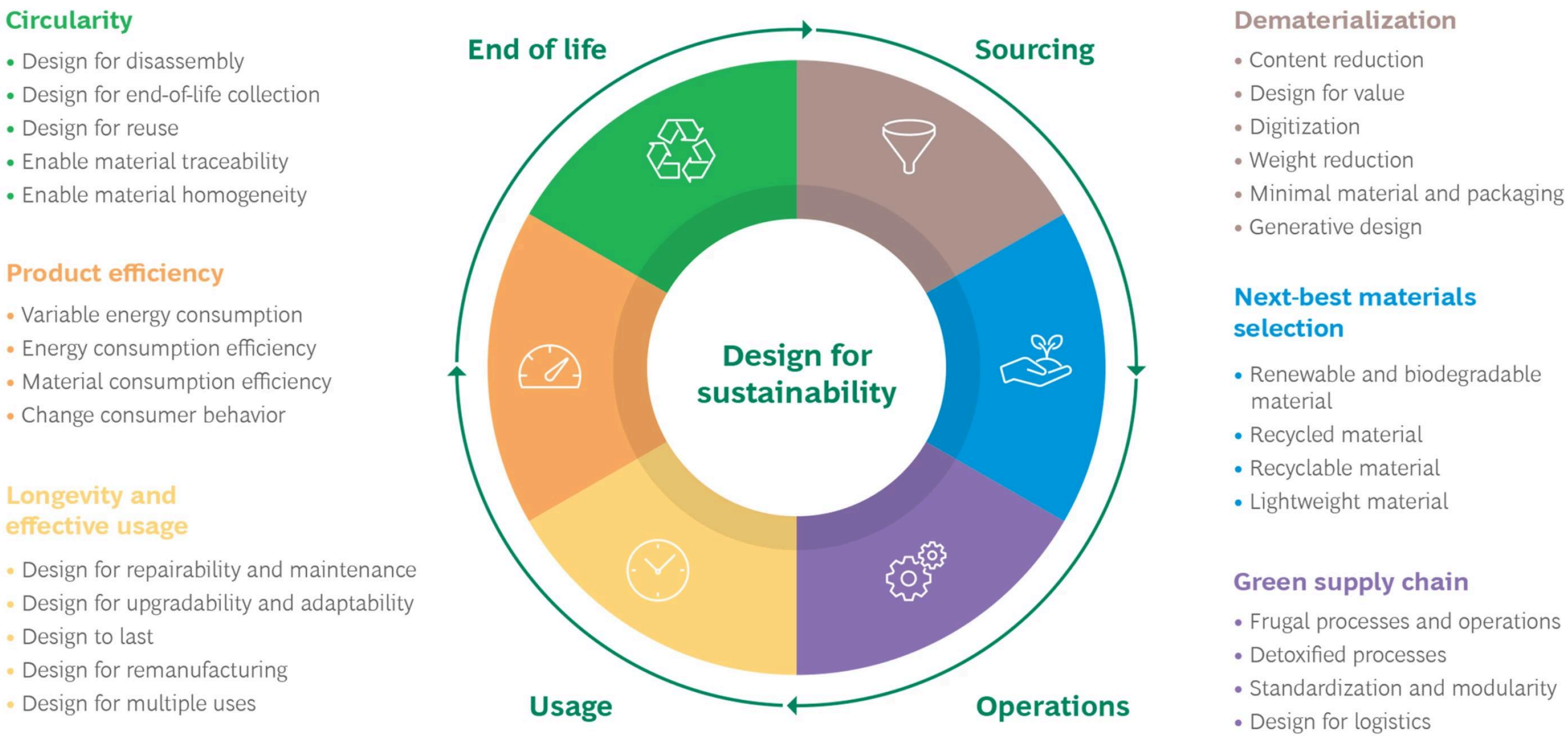


Figure 13: Sustainable design strategies over the full life-cycle of a product (Mouëllic et al., 2023)

Green supply chain

The manufacturing processes related to the material replacement should contain minimum toxic processes. This does not only improve the supply chain's sustainability, it also decreases the chance of pollution causes by toxic material components.

The redesign should fit standard palettes to optimise logistics, reducing the carbon footprint.

Clinker manufacturing for cement used in concrete requires temperatures up to 1450 °C, requiring large amounts energy, mainly from fossil fuels (Monteiro et al., 2017; Miller et al., 2016; Müller & Harnisch, 2008). Manufacturing the material of the redesign should require as little energy as possible to be sustainably competitive with concrete.

Longevity and effective use

Plastic degradation produces harmful particles. With GP being in direct contact with soil and water, the material of the redesign should produce no contaminating or toxic particles or chemicals during use of the product. Additionally, plastics are likely perceived as unsustainable by municipalities, as obtained from an interview (section 4.1.3.3).

GP modules with reversible connections allow for maintenance to increasee the lifetime of the public space. Additionally, it allows for disassembly to accomodate maintenance to cables and plumbing that is situated below the infrastructure.

Product efficiency

GP reintroduces or increases vegetation in urban areas. Combining vegetation with infrastructure might show inhabitants of urban areas the contrast between vegetated and over-paved areas. It might restore the relation of people in urban areas with nature. Increasing how much inhabitants of urban areas value vegetation in urban areas could increase the inclusion of vegetation, improving the climate adaptive qualities of cities.

Circularity

If the public space nevertheless is redecorated completely, the GP modules with reversible connections can be disassembled and reused elsewhere.

To improve material traceability, the material replacement should contain as little components as possible.

4.2.2 Manufacturing

Prototyping with a potential material is desired for this study, therefore material should be available and processable considering the skill, costs and equipment.

Prototyping with the material will be done in the Materials Lab of Industrial Design Engineering at the TU Delft. The required materials should be obtainable and safe to process in the Lab. The costs of materials should be as low as possible to promote multiple iterations.

In the Materials Lab, a heat press, oven, microwave, bench drill, granulator and hand tools are available. The equipment required for prototyping with a material should be available in the Lab.

Since permeable pavement is used for applications such as parking lots, manufacturing should be scalable. This means production can increase in volume without problems arising in material sourcing or limitations in manufacturing processes.

4.2.3 Mechanical properties

Mechanical properties are screened to deem a material 'strong enough' for GP.

TAWWA Grids currently meet the load capacity standard SLW60 according to DIN1072 (Tonn, 2023), which describes a static load (uniconstruct, n.d.; Spyrakos et al., 2017). As vehicles accelerate, decelerate and change direction it would be assumed that a dynamic load standard would be met. However, this study, similar to the current standard, focuses on a static load. This simplifies testing of material samples and modeling of the redesign.

When a force is loaded onto a material, it creates stress (force per area). Sufficient stress can transform the dimensions of a material, called deformation. Comparing the original with the deformed dimensions explains the strain caused by the stress. The Young's modulus (E) explains the relationship between stress and strain (The Efficient Engineer, 2024; (Admin, 2025). A higher E means an equal amount of stress causes less strain, making the material more stiff (Admin, 2025). Stress up until the Yield Strength (YS) of the material causes elastic deformation, meaning the material returns to its original shape when the load is released (The Efficient Engineer, 2023; Admin, 2025). When the stress surpasses the YS, deformation becomes permanent, called plastic deformation (The Efficient Engineer, 2023; Admin, 2025). When an even higher stress surpasses the material's Ultimate Compressive Strength (UCS) the material fractures, also called failure (The Efficient Engineer, 2023; Admin, 2025).

Ductile materials can handle a high degree of plastic deformation before failure, while brittle materials have little to no plastic deformation and fail at low strains (The Efficient Engineer, 2023; Admin, 2025). Plastic is ductile while concrete is brittle. Due to the limited plastic deformation of brittle materials, identifying the Yield Strength is sensitive to inaccuracy. Ordinary brick and high-strength concrete have a UCS of roughly 22.2 MPa and >42 MPa, respectively (Roberts & Scrutton, 2023). The UCS of brittle materials and the YS of ductile materials should be at least 22.2 MPa.

4.3 Potential Alternative Materials

Plastics from renewable sources, compressed earth, mycelium and concrete from bio-cement were considered as a sustainable material replacement for GP.

Figure 14: A coffee cup made from coffee grounds (Coffee Based, 2025)

Bioplastics are a group of materials either sourced from renewable materials, converts into natural substances through biodegradation or both (Figure 14) (European Bioplastics, 2023). Bioplastics offer similar properties as fossil-based plastics while producing biomass captures carbon (Stora Enso, n.d.). However, if not disposed of properly, plastic particle pollution remains a threat, polluting the earth, affecting human and animal health (Karidis, 2024).

Figure 15: Mycelium floor boards with a bio-based top layer (Mogu SRL, 2023)

Mycelium is the root-like structure of fungi, composed of microscopic threads called hyphae (Figure 15) (Van Der Hoeven, 2020). It serves as the foundation for mushroom growth and can be cultivated into sustainable materials for various applications, including construction (Van Der Hoeven, 2020). Mycelium manufacturing transforms agricultural waste into useful material, while being energy efficient (Van Der Hoeven, 2020). However, mycelium growth is time-intensive and the material is not considered for structural elements (Van Der Hoeven, 2020).

Figure 16: Cow dung stabilised earthen bricks (The Green Village, 2023)

When earth is pressurized, blocks can be formed which are capable of withstanding compressive loads. These blocks can be waterproofed by mixing in fresh cow manure (Figure 16) (Yask Kulshreshtha, 2022). However, the material decomposes when put in the ground (Yask Kulshreshtha, 2022). Additionally, prototyping with fresh cow dung was not possible due to risk of diseases.

Figure 17: Tiles made with bio-cement (FRONT® Materials, 2024)

Bio-cement rely on bacteria and organisms to form a renewable cement alternative (Prometheus Materials, 2023; Biomason, 2024). This can result in concrete with a negative carbon footprint (Figure 17) (Biomason, 2024). However, bio-cement technologies are novel, expensive and complex, making it unsuitable for this research.

CoRncrete is a material made from water, sand and starch (Figure 18) (Kulshreshtha et al., 2017; Roberts & Scrutton, 2023), all readily available resources. Starch is a cost-effective and biodegradable biopolymer derived from photosynthetic tissue of plants, a renewable resource (Roberts & Scrutton, 2023; Kulshreshtha et al., 2017). Sand is a non-toxic, non-contaminating material with the potential to be sourced from demolition waste. CoRncrete manufacturing machinery includes a microwave, an oven and a hydraulic press, depending on the exact manufacturing process (Figure 19). Kulshreshtha et al. (2017) produced CoRncrete with an ultimate compressive strength of up to 26.67 MPa. Through additives, Roberts & Scrutton (2023) produced a CoRncrete inspired material with a UCS of 72.0 and 91.7 MPa, respectively (Figure 20). This shows CoRncrete has the technical potential to compete with current pavement solutions, while posing as a sustainable alternative.

Figure 19: CoRncrete manufactured in the microwave (InstrucTables, 2017)

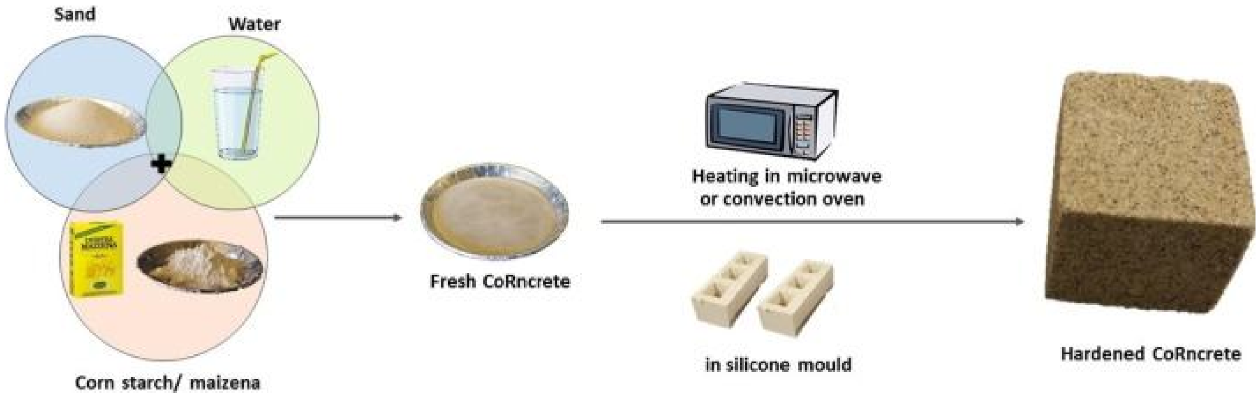


Figure 18: CoRncrete manufacturing as proposed by Kulshreshtha et al. (2017)

Figure 20: StarCrete manufactured by Roberts & Scrutton (2023)

4.4 Current state of CoRncrete

CoRncrete is a construction material developed by Kulshreshtha et al. (2017) formed by mixing sand, cornstarch and water and heating it in the microwave or oven (Figure 21). Starch dissolved in water transforms through heating into a 'glue' that binds the sand, creating a hardened material after dehydration (Kulshreshtha et al., 2017; Roberts & Scrutton, 2023). This process is called gelatinisation (Kadam et al., 2015), a process predominantly dependent on starch type, amount of water and heating temperature (Kulshreshtha et al., 2017). Current research has focused on improving manufacturing and waterproofing (Figure 22).

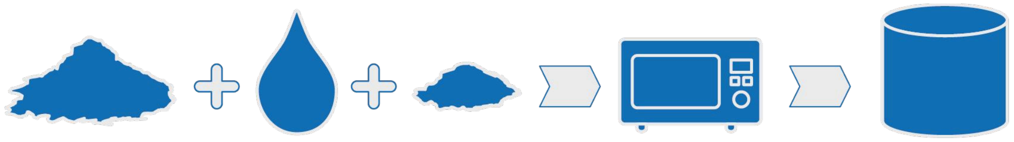


Figure 21: CoRncrete production as proposed by Kulshreshtha et al. (2017)

4.4.1 Starch

Kulshreshtha et al. (2017) applied cornstarch to form the innovative CoRncrete. Starch is sourced from the photosynthetic tissue of plants (Kulshreshtha et al., 2017). Starch has extensive applications within construction, including use as a concrete additive (Kulshreshtha et al., 2017; Tulip et al., 2023). The research of Mansour et al. (2020) and Tulip et al. (2023) further researched this innovation without altering the starch source.

Starch gelatinisation is an irreversible, endothermic process that occurs when starch is heated in the presence of water (Kadam et al., 2015). The structure of starch is transformed in this process, enabling its binding properties (Kadam et al., 2015). This transformation in the presence of sand creates CoRncrete (Kulshreshtha et al., 2017). The extent to which starch is transformed through gelatinisation, or gelatinisation rate, is depedent on starch type, amount of present water, and heating temperature (Khulshreshtha et al., 2017). An increased gelatinisation rate improves the strength of CoRncrete through improved bonding in the microstructure (Khulshreshtha et al., 2017).

4.4.2 Sand

Kulshreshtha et al. (2017) compared CoRncrete manufactured using sand with a grain size of 0.125 - 0.250, 0.250 - 0.500, 0.500 - 1.000 and 1.000 - 2.000 mm. The CoRncrete was manufactured in the oven and microwave, but regardless of the source of heating, "with an increase in sand grain size, compressive strength decreases" (Khulshreshtha et al., 2017). Khulshreshtha et al. (2017) speculates a reduced surface area of sand interacting with starch and an increased distance between sand grains causing micro cracks causes this behaviour of CoRncrete. Using Kulshreshtha et al. (2017) as a basis for further research on CoRncrete, Mansour et al. (2020) similarly used 0.125 - 0.250 mm sand for sample manufacturing. Tulip et al. (2023) manufactured CoRncrete samples with sand grains measuring 0.106 - 250 and 0.250 - 0.425 mm. In contrast to Kulshreshtha et al. (2017), they found a coarser sand grain size, 0.250 - 0.425 mm, improved compressive strength (Tulip et al., 2023). This difference is likely caused by the different heating pattern of the oven compared to the microwave, according to Tulip et al. (2023).

4.4.3 Ingredient Ratios

The relationship between the amount of water and starch affects the gelatinisation process. Kulshreshtha et al. (2017) found 15% and 16.66% water content to be the optimum water content for CoRncrete manufactured in the microwave and oven, respectively. Based off the findings of Kulshreshtha et al. (2017), Mansour et al. (2020) manufactured CoRncrete samples with a 1:1:5 starch, water and sand ratio. Similarly, Tulip et al. (2023) concluded a starch, water and sand ratio of 1:1:5 as optimal for CoRncrete manufacturing in the oven.

4.4.4 Heating

The heating duration and rate at which energy is added affect the gelatinisation process of CoRncrete (Khulshreshtha et al., 2017). Microwaves use electromagnetic waves which heat the water molecules inside the wet CoRncrete mixture (Whirlpool, 2020). Heating elements increase the temperature of an oven chamber, with optional fans for air circulation to promote homogeneous heating (Maytag, 2023). Kulshreshtha et al. (2017) compared microwave and oven heating and concluded that manufacturing CoRncrete in the microwave improves compressive strength compared to oven heating.

Ovens have a slow heating rate, potentially leading to water evaporation before gelatinisation, reducing the degree of gelatinisation in samples. Alternatively, microwaves allow for a high heating rate, reaching the gelatinisation temperature quickly (Khulshreshtha et al., 2017). The oven creates uneven heating as the temperature of the sample increases gradually, resulting in relatively heterogeneous gelatinisation (Khulshreshtha et al., 2017). Microwaves reach higher temperatures compared to ovens, improving gelatinisation and strength development (Khulshreshtha et al., 2017).

However, Tulip et al. (2023) argues that microwave are expensive and do not allow scaling up to mass production of CoRncrete products. Though microwave manufacturing produces CoRncrete with higher strength, this makes oven manufacturing of CoRncrete desirable for GP design.

Kulshreshtha et al. (2017) heated the samples in the microwave for 1.5 minute in thaw mode followed by 3.5 minutes in high power mode. This scheme added 19.8 kJ of energy in 1.5 minute and 231 kJ over 3.5 minutes. Mansour et al. (2020) similarly, heated the samples for 1.5 minutes in thaw mode and 3.5 minutes at high power mode, but used a 800W microwave compared to the 1100W model used by Kulshreshtha et al. (2020).

Kulshreshtha et al. (2017) heated the samples for 24 hours at 105 °C in the oven, while Tulip et al. (2023) found 110 °C for 24 hours to be optimal.

4.4.5 Mechanical properties

The sand grain size, ingredient ratios and heating method strongly influence the mechanical performance of CoRncrete (Khulshreshtha et al., 2017; Tulip et al., 2023). Kulshreshtha et al. (2017) found a UCS of up to 26,67 MPa, whereas Mansour et al. (2020) found a compressive strength of roughly 30 MPa in samples prepared in the microwave. Kulshreshtha et al. (2017) manufactured samples with a UCS of 13,70 MPa using the oven, while Tulip et al.'s (2023) oven samples resulted in a UCS of 18,9 MPa.

4.4.7 Sustainability

CoRncrete includes renewable starch and can be recycled (Kulshreshtha et al., 2017). An LCA performed by Kulshreshtha et al. (2017) revealed CoRncrete has a higher eco-cost than Concrete or Brick. This is mainly caused by consumption of chemical fertiliser, pesticides, energy and water for growth of corn crops resulting in increased eco-toxicity and risks to human health (Kulshreshtha et al., 2017). Alternatively, CoRncrete has a comparable carbon footprint as concrete, and lower compared to bricks (Kulshreshtha et al., 2017). Reducing the amount of starch, improving crop cultivation sustainability and increasing the product lifetime will likely improve the eco-cost of CoRncrete (Kulshreshtha et al., 2017).

4.4.8 Pigmentation

In an instructional video, ASU Open Door (2021) highlighted the pigmentation potential of CoRncrete. Adding food coloring in the water before mixing with the sand and starch, allowed for homogeneous pigmentation, altering the appearance of CoRncrete (ASU Open Door, 2021).

4.4.9 Degradability

CoRncrete coming in contact with water, naturally breaks the material down into smaller components, meaning it is biodegradable (Kulshreshtha et al., 2017; Mansour et al., 2020). This can pose sustainable benefits but makes CoRncrete less durable as a construction material. Exposing CoRncrete to water results in degradation within a day when submerged completely (Kulshreshtha et al., 2017; Mansour et al., 2020). An increased starch gelatinisation rate significantly improves the water resistance of CoRncrete (Kulshreshtha et al., 2017). Additionally, Mansour et al. (2020) aimed to improve the water resistance through the application of coatings, both natural and synthetic. While coatings, such as Silres BS 4004, KSE 100, and carnauba wax, merely extended durability to 5-7 days, others, like pure beeswax, paraffin wax, and tristearin, preserved structural integrity for up to 15 days (Mansour et al., 2020).

Research	Kulshreshtha et al. (2017)	Mansour et al. (2020)	Tulip et al. (2023)
Goal	'Invention' of CoRncrete. Optimum composition and heating for oven and microwave	Improving Microwave manufacturing and adding waterproofing coating	Improving Oven manufacturing to improve scalability
Optimal sand	0.125 - 0.250 mm	0.125-0.250 mm	0.250-0.425 mm
Manufacturing	Microwave and Oven	Microwave	Oven
Technical data	Microwave: 26,67 MPa UCS Oven: 13,70 MPa UCS	30 MPa UCS	18.9 MPa UCS

Figure 22: Current CoRncrete research (Kulshreshtha et al., 2017; Mansour et al., 2020; Tulip et al., 2023)

4.5 StarCrete

Due to the minimal amounts of water present on the Moon and Mars, Roberts & Scrutton (2023) developed a material called StarCrete, based on CoRncrete. Roberts & Scrutton (2023) propose StarCrete for the construction of extraterrestrial habitats because of the uncomplicated and low-energy manufacturing process. Additionally, the resources are abundantly available as starch is renewable and can be cultivated in long-term habitats, the water content can largely be recovered and Mars and Moon dust can replace sand (Roberts & Scrutton, 2023). Based on this research, two videos explain manufacturing of StarCrete using the microwave and using an optimised manufacturing process (Aled Roberts, 2022; Aled Roberts, 2023).

Roberts & Scrutton (2023) inquired the binding strength of multiple starch sources: Maize, Waxy maize, Tapioca, Potato, Wheat, Rice, and Waxy rice. Potato starch showed 'clear superiority' compared to other starch sources in preliminary testing (Roberts & Scrutton, 2023). Roberts & Scrutton (2023) highlight the "relatively viscous paste upon gelatinisation" as a potential explanation for this result. Additionally, relative to other starch sources, potato starch has large starch granules, a low gelatinisation temperature, very low protein and fat content and high phosphate content (Roberts & Scrutton, 2023). Due to the incorporation of potato starch in stead of cornstarch, the material was renamed to StarCrete, referring to starch and concrete (Roberts & Scrutton, 2023).

In stead of sand, Roberts & Scrutton used Mars and Moon minerals in a CoRncrete-based material. Mars and Moon minerals comprise of terrestrial mineral compositions based on data from Mars and Lunar expeditions (Space Resource Technologies, n.d.). According to Aled Roberts (2023) a reproducible substitute can be achieved by adding 9% dry, fine clay and 1% iron oxide to sand. However, no data regarding sand grain size was mentioned.

Kulshreshtha et al. (2017) and Tulip et al. (2023) used tap water, introducing location-specific minerals. Alternatively, Roberts & Scrutton (2023) used demineralised water, which is filtered of most minerals and salts, to improve the reproducibility of the samples (Techniekwebshop.nl, 2021).

Roberts & Scrutton (2023) explored the effect of additives on the UCS of StarCrete. Through context relevance, Urea, MgCl2, Acetic acid, FeSO4, Na2CO3 and Human saliva were included in the study (Roberts & Scrutton, 2023). Roberts & Scrutton found that including Magnesium Chloride (MgCl2) significantly improved the UCS.

100 grams of Mars dust or 90 grams of sand, 9 grams of clay and 1 gram iron oxide are added to 5.82 grams of potato starch (Aled Roberts, 2022; Roberts & Scrutton, 2023). Aled Roberts (2022) explains how 1.48 grams of $MgCl_2$ is dissolved in 21.77 ml demineralised water. However, Roberts & Scrutton (2023) add 2.79 grams of a 0.5 Mol $MgCl_2$ solution. The dehydrated gelatinised mixture is rehydrated with 5% water (Aled Roberts, 2022).

Perhaps most noteworthy is the finding of Roberts & Scrutton (2023) that after gelatinisation, the mixture can be fully dehydrated and rehydrated without negatively affecting the UCS. This resulted in an alternative manufacturing technique, where a hydraulic press is included for final shaping and bonding of the material (Figure 23). This modification allows a separation in the water content of the mixture in the gelatinisation and final forming steps (Roberts & Scrutton, 2023). A high water content benefits the gelatinisation rate, while a low water content benefits the process of final forming (Roberts & Scrutton, 2023).
Aled Roberts (2022) and the Supplementary material of Roberts & Scrutton (2023) explain the modified manufacturing in detail. Potato starch and Mars dust are mixed together (Aled Roberts, 2022). Magnesium Chloride is dissolved in water and added (Aled Roberts, 2022). The mixture is heated in the oven for 120 minutes at 120 °C in a closed container to reduce water evaporation, improving gelatinisation (Aled Roberts, 2022; Roberts & Scrutton, 2023). After gelatinisation the mixture is divided into fractions to increase the surface area, accelerating dehydration (Aled Roberts, 2022). The gelatinised mixture is dehydrated in the oven for 60 minutes at 90 °C and crushed into a powder (Aled Roberts, 2022; Roberts & Scrutton, 2023). The mixture is rehydrated, mixed and put into the mould before final forming under 22 MPa of pressure (Aled Roberts, 2022).

StarCrete with Mars and Moon minerals has a UCS of 72.0 and 91.7 MPa, respectively.

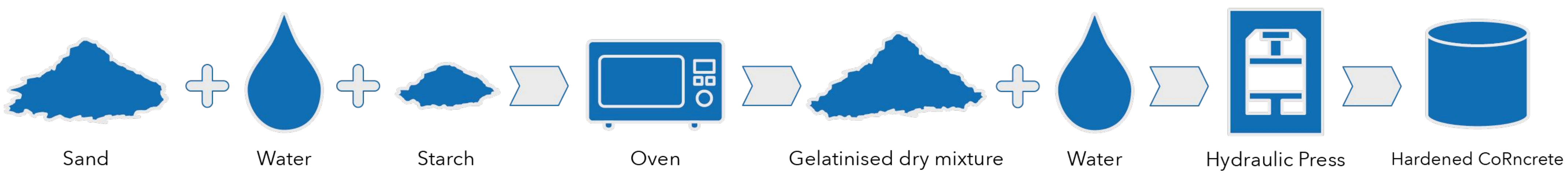


Figure 23: Simplified CoRncrete production as proposed by Roberts & Scrutton (2023)

4.6 Conclusion

CoRncret is a material with potential for GP manufacturing, while providing sustainable benefits. Current research has manufactured CoRncrete in lab settings. CoRncrete was originally manufactured in the oven or microwave, with microwaves providing strength benefits and ovens a scalability benefit. Roberts & Scrutton (2023) proposed an alternative manufacturing process with scalability and strength improvements.

4.6.1 Research goal

Roberts & Scrutton (2023) concluded potato starch to be the most optimal starch type. Exploring starch types in combination with microwave and oven manufacturing can provide interesting findings. Kulshreshtha et al. (2017) and Tulip et al. (2023) found contradicting trends in relation to sand grain size while both concluding a strong correlation between material strength and sand grain size. Roberts & Scrutton (2023) did not identify an optimal sand grain size for hydraulic press manufacturing, proving an opportunity for further improving the manufacturing process. Due to the specific benefits of each manufacturing process, all are considered in this research. This research limits additives to safeguard sustainability and streamline prototyping. Future research has the chance to add functionality through additives, while this study provides a base material. An additional challenge for CoRncrete applications is the moisture sensitivity (Kulshreshtha et al., 2017; Mansour et al., 2020; Roberts & Scrutton, 2023). However, due to the added complexity of material testing and introduction of multiple additives, waterproofing is not included in this research. The technical goal of this research is to:

*Research CoRncrete **components** and **manufacturing processes** that improve **scalability**, **quality** and **sustainability** and assess their impact on the **mechanical properties** of CoRncrete*

Materialisation with existing materials allows designers to include the user experience in their decision making. CoRncrete is a material developed and researched in lab settings as the applications are yet viewed as limited, though Roberts & Scrutton (2023) see extraterrestrial habitat potential. CoRncrete has not been used in products nor have experiential characteristics been researched prior to this study. In order for CoRncrete GP to be desirable, the material's experiential characteristics should be considered. Therefore, the experiential goal of this research is to:

*Identify the **experiential characteristics** of CoRncrete to design a GP **user experience** fitting the **context** as well as the **material***

4.6.2 Requirements and wishes

Requirements and wishes regarding scalability, material quality and sustainability can be concluded from current research.

Material Scalability

- Manufacturing should be reproducible
- The material components should be readily available
- Manufacturing equipments should be readily available

Material quality

- The UCS of CoRncrete should be at least 22.2 MPa
- The gelatinisation rate should be as high as possible

Material Sustainable

- The material should contain a minimal amount starch
- The material should contain a minimal amount of different components
- Manufacturing processes should use as little energy as possible
- During use, the product should not leach any toxins
- During use, the product should not produce polluting particles
- Downcycling the material should be possible
- The material should be as light as possible

Redesign

- The redesign should be as light as possible
- The connections of the redesign should be reversible
- The redesign should fit standard palettes
- The redesign should aim to connect people with nature
- The redesign should emphasise the material's user experience

5 tinkering

What is CoRncrete's behaviour under different conditions?

- *How does CoRncrete manufacturing become scalable?*
- *How is high-quality CoRncrete manufactured?*
- *How does CoRncrete manufacturing remain sustainable?*

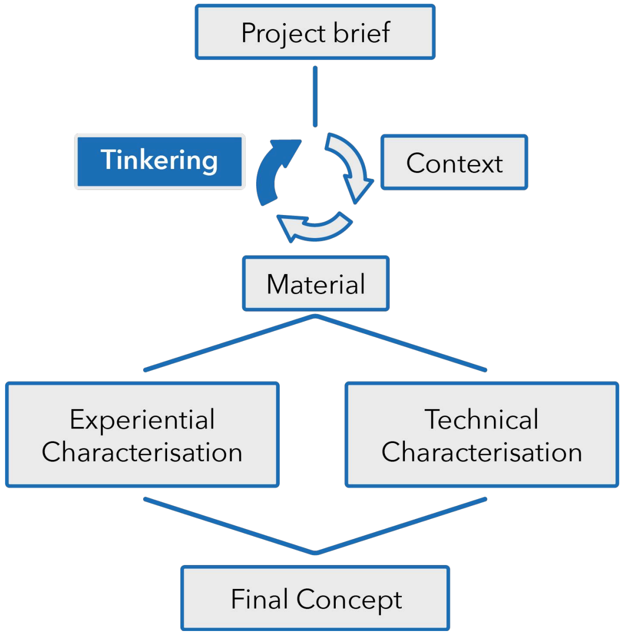


Figure 24: Tinkering section in the project structure

This chapter explains the process of understanding CoRncrete under varying conditions through experience with the manufacturing processes. 'Tinkering' aims to find material mixes, activities and equipment that improve the speed, quality and sustainability of CoRncrete manufacturing. Understanding CoRncrete manufacturing in a lab setting allows to extrapolate the processing findings to factory scale production of CoRncrete products.

5.1 Method

5.1.1 Materials

CoRncrete can be made using different constituents (Kulshreshtha et al., 2017; Roberts & Scrutton, 2023). Replicating existing studies (Kulshreshtha et al., 2017; Mansour et al., 2020; Tulip et al., 2023; Roberts & Scrutton, 2023), cornstarch and potato starch were included. Tapioca starch was also included in the study as previously done by Roberts & Scrutton (2023). Cornstarch from Maizena from Duryea was bought at the Albert Heijn. Potato starch from Van Beekum Specerijen was bought from their online store (vanbeekumspecerijen.nl). Tapioca starch from Joannusmolen was bought at the Ekoplaza. Sand with four different grain sizes were used. Sand with grain size 1 – 2 mm from Stonewish was bought at the Gamma. Sand with grain size 0.125 - 0.250, 0.250 – 0.500 and 0.500 – 1,000 mm was used from the Microlab of the faculty of Civil Engineering. Tap water in the city center of Delft, The Netherlands and demineralized water from Boom was used.

A domestic kitchen and the Materials Lab at the faculty of Industrial Design Engineering accommodated the tinkering process. A kitchen scales and Kern EMB 2000-2 scales were used for measuring the different constituents (Figure 25).

Figure 25: A kitchen scales (left) and Kern EMB 2000-2 scales (right)

Tools for mixing (e.g., spoons, forks, whisks) and containers (e.g., measuring cups, bowls) were readily available at both facilities. Additionally, a Tomado TM-2439 electrical hand mixer with two different attachments was available in the Materials Lab (Figure 26) .

Figure 26: A Tomado TM-2439 electrical hand mixer with two different attachments

A pipette was available at the Materials Lab for dosing water (Figure 27). A hammer was used for pulverisation of the dehydration mixture.

Figure 27: A plastic pipette from the Materials Lab

Three different manufacturing processes were used for tinkering. As proposed first by Kulshreshtha et al. (2017) and copied by Mansour et al. (2020), samples were heated in a microwave. A Whirlpool GT288 and Tarrington House MWD5130 (Figure 28) microwave were used. As first proposed by Kulshreshtha et al. (2017), improved upon by Tulip et al. (2023) and adapted by Roberts & Scrutton (2023), samples were made in a Memmert UF75 convection oven (Figure 29). Additionally, the manufacturing process as proposed Roberts & Scrutton (2023) requires a Hydraulic Press, for which a Carver Heat Press, without use of the heating, was used (Figure 30).

Figure 28: Tarrington House MWD5130 microwave

Figure 29: Memmert UF75 convection oven

Figure 30: Carver Heat Press

In the microwave, two different silicon moulds were used (Figure 31). Making CoRncrete samples in the oven, an aluminium mould was used (Figure 32). For gelatinisation, a round silicon mould was used (Figure 33). Oven trays were used for the dehydration process. In the hydraulic press, an aluminium mould with two pistons was used (Figure 34).

Figure 31: Silicon moulds used in the microwave

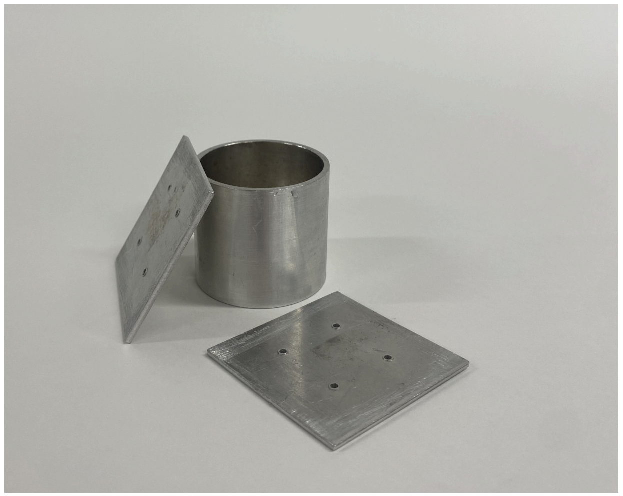


Figure 32: Aluminium oven moulds

An electrical sanding belt (Figure 35) and a hacksaw (Figure 36) were used for post-processing.

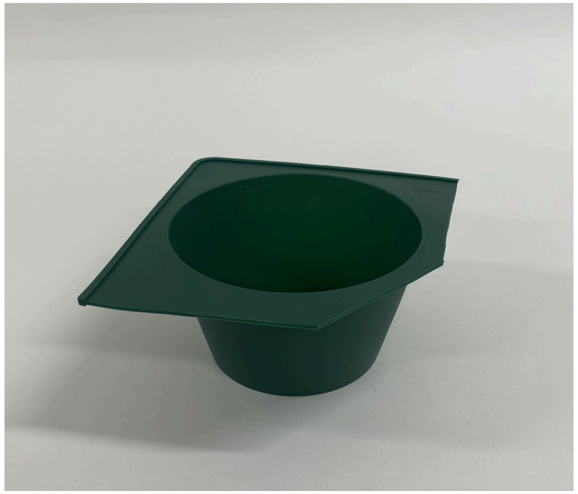


Figure 33: Round silicon moulds used in the oven

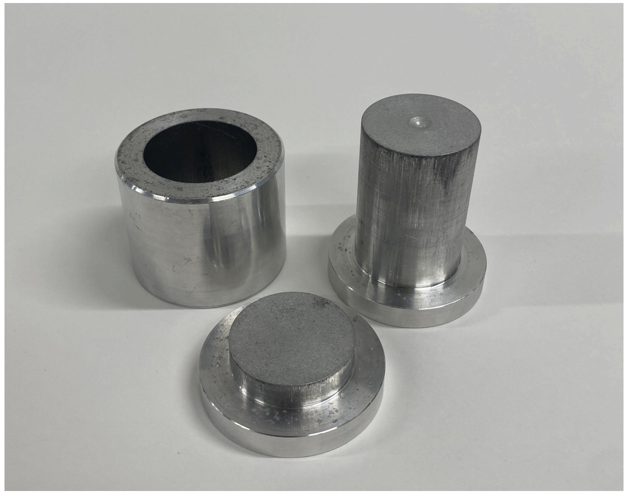


Figure 34: Aluminium mould for the hydraulic press

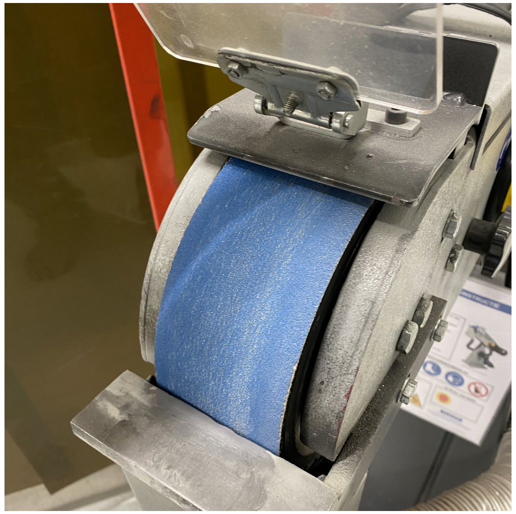


Figure 35: Sanding belt pic

Figure 36: Hacksaw pic

5.1.2 Sample coding

The samples produced in tinkering were labelled according to a coding system for recognising the samples and structuring the data collected in later testing. The sample code consists of three letters followed by a number. The first letter represents the manufacturing technique (Table 2). The second letter represents the size of the sand grains used in the sample (Table 3). The third letter denotes the starch type used in the sample (Table 4). The number at the end of the code denotes the chronological order in which samples with the same constituents are made (Table 5). Table 6 shows how sample PMP2 is coded using the coding system.

Manufacturing process	Code
Microwave	M
Oven	O
Oven and Hydraulic Press	P

Table 2: Code for manufacturing process

Sand Grain Size (mm)	Code
0.125 - 0.250	F (fine)
0.250 - 0.500	M (medium)
0.500 - 1.000	C (coarse)
1.000 - 2.000	G (gamma)

Table 3: Code for sand grain size

Starch type	Code
Cornstarch	C
Potato starch	P
Tapioca starch	T

Table 4: Code for starch type

Chronological order	Code
First sample	1
Second sample	2
Etc.	Etc.

Table 5: Code for chronological order

	Manufacturing process	Sand Grain Size	Starch type	Chronological order
Full name	Oven and hydraulic press	0.250 - 0.500 mm	Potato starch	Second sample
Code	**P**	**M**	**P**	**2**

Table 6: From full name to code for PMP2

5.2 Manufacturing process

Through tinkering, each step of CoRncrete manufacturing was performed, evaluated and improved upon until an optimal process was concluded. This optimal process is scalable to factory manufacturing for large scale manufacturing of CoRncrete products.

5.2.1 From ingredients to wet mixture

First, a decision is made on the type of sand and starch, which are weighed and mixed together, turning into the dry mix. Water is weighed, added and mixed to create the wet CoRncrete mixture or wet mix.

The Gamma sand contained pieces of gravel exceeding 2 mm. As heterogeneous sand could lead to inconsistent results, uniform sand was retrieved from the Microlab at the faculty of Civil Engineering at the TU Delft.

The kitchen scales required the weight of constituents to be rounded off as the scales measured in whole grams. To improve the accuracy and consistency of the mixtures, a Kern EMB 2000-2 scales was available in the Materials Lab. Using this scales and spoons allowed for measurements of the dry components accurate to two decimals.

As previously found by Kulshrestha et al. (2017) and Tulip et al. (2023), the starch and sand need to be mixed separately first, to remove clutters. The dry mix was best mixed using a whisk, compared to using a fork and the electrical mixer. A whisk was more efficient and scalable than using a fork at obtaining an even dry mix (Figure 37). Conversely, the electrical mixer was too aggressive and caused the starch to blow out of the mixing bowl.

Samples made in the residential kitchen contained tap water, while demineralised water was used in the samples made in the Materials Lab as it was available and would improve the reproducibility of the study results.

Weighing water was initially done by pouring demineralized water from a smaller container into a container on the scales. However, this led to inaccurate measurement, so a plastic pipette similar to Figure 27 was used, allowing addition of water accurate to two decimals.

Using the Tomado TM-2439 electrical hand mixer allowed for thorough mixing of the wet mix, especially mixing larger volumes. Initially, the mixer attachments with a lot of open space were used (Figure 26-left), however they flung the wet mix aggressively, losing parts of the wet mix. Dough hooks (Figure 26-right) were more subtle and mixed the bottom of the wet mix increasingly well (Figure 37).

Mixing the wet mix with 14.29% and 15.25% water content, the mixture would fragment into separate sand clumps when mixed hard. However, when no stress was applied the wet mix would 'melt' together, acting like a liquid, allowing the wet mix to be poured. This behaviour is described as Shear Thickening, where the viscosity of the material increases with increased stress (Science Learning Hub, 2010). Fluids with this behaviour are called non-Newtonian fluids (Science Learning Hub, 2010). Whereas wet mixes with 13.29% water content behaved less like liquids, increasing the water content above 14.29% did not improve the ability to pour the wet mix.

When scaling the amount of samples made from one batch of wet mix, making too much CoRncrete mixture is more convenient than making too little. The mixing and various transfers between containers increase the potential losses of wet mix. The weight to volume ratio was important to ensure filling each mould completely. 500 grams of wet mix filled the rectangular silicon mould of 260 ml. 40 by 40 mm cylindrical samples with a volume of 50.27 ml were manufactured in the oven from 120 grams of wet mix. 375 grams of wet mixture resulted in three cylindrical samples of 50.27 ml each using the hydraulic press.

Figure 37: Most efficient dosing and mixing tools

5.2.2 Moulds

The wet mix is poured into a mould and the mould is put into a microwave or oven to gelatinise the starch. From here two options arise, either the CoRncrete is heated until most of its water content is evaporated and a hardened CoRncrete sample is achieved or the wet mix is heated until gelatinised and taken out of the oven as a gelatinised wet mix, requiring further processes to reach a hardened sample.

Filling the mould was best done in layers, tamping each layer, to remove air pockets from the wet mix. Kulshrestha et al. (2017) and Tulip et al. (2023) used a tamping rod, coming to the same conclusion. The Non-Newtonian wet mixes could be easily poured and spread evenly throughout the mould, making 14.29% the minimum ideal water content.
A rectangular and cupcake silicon mould were used in the microwave. These were readily available for quick tinkering and allowed for easy demoulding due the material's flexibility.

Standardised sample dimensions allow for mechanical testing later in the process. The sample dimensions were based on the 40 by 40 by 40 mm cubes produced by Mansour et al. (2020). Instead of cubes, cylindrical samples were considered more optimal for later compressive testing.

For the oven mould, aluminium was used as this would provide a sturdy structure with high thermal conductivity, creating an equal heat distribution in the oven (Tilcon, 2024). Additionally, aluminium is a cost-effective material that can be shaped with milling and turning. The 40 mm high cylinder is turned out of solid aluminium rod to a 2 mm wall thickness. 2 mm thick base and top plates prevented potential deformation and allowed for easy extraction of the hardened sample, inspired by Tulip et al. (2023). Four 2-mm holes were added to the plates for evaporation, resulting in a hardened material. The mould was filled in layers, tamping each and excess wet mix was scraped off the top with a knife. The base and top plate were securely fastened using a metal clamp (Figure 40).

To create the gelatinised wet mix, the material does not require hardening during heating allowing more water to be present compared to the oven and microwave. The increased amount of water could increase the gelatinisation rate, improving the binding abilities of starch (Roberts & Scrutton, 2023).
Roberts & Scrutton (2023) heated glass jars with aluminium caps at 120°C for 120 minutes but noted that "the glass vials sometimes explode due to excessive pressure". Aled Roberts (2022) uses a 250 ml Simax lab bottle made of borosilicate glass, resistant up to 140°C (Glazen-en-Potten.nl, n.d.). The Materials Lab had similar borosilicate glass bottles with a volume of 500 ml and 1000 ml, resistant up to 140°C (DURAN®, n.d.). Though borosilicate glass can reach high temperatures, it is still able to shatter due to pressure.
A pilot test was done leaving the 500 ml bottle open and covering the 1000 ml bottle with aluminium foil. The CoRncrete in the 500 ml bottle hardened, making it impossible to remove the material from the bottle. In contrast, the aluminium foil 'lid' avoided pressure build-up while preserving moisture, creating a wet gelatinised mix. However, due to the size and shape of the bottle, removing the wet gelatinised mix from the bottle was difficult and the sand scratched the glass.
A round silicon mould was eventually used as this would allow for easy demoulding as concluded from microwave manufacturing (Figure 38). An aluminium foil lid was used to reduce evaporation (Figure 38).

40 by 40 mm cylindrical samples were manufactured in the hydraulic press. Aluminium was used for the mould as it can be shaped well, is lightweight and inexpensive. A hydraulic press mould consists of two parts, a chamber and a piston. The chamber is an aluminium cylinder measuring 50 mm high, with an inner diameter of 40 mm and a wall thickness of 10 mm. The excess height allows the piston to compress more mixture as the volume decreases under pressure. Two pistons of varying sizes were used. A long piston measuring 58 mm in length is used for initial compression and for extracting the samples for the chamber. A short piston measuring 10 mm in length creating a 40 mm sample when the small piston is fully inserted into the bottom cylinder. Both pistons are 39 mm in diameter to allow smooth insertion. Additionally, the top of the chamber features a chamfered inner edge for easier alignment. Aligning the top of the piston with the chamber walls ensures a level top surface of the samples.

Figure 38: Aluminium foil lid on a silicon mould used for gelatinisation in the oven

5.2.3 Heating processes

Heating was done to create hardened CoRncrete in the microwave or oven or to create a gelatinised mix in the oven.

The amount of power and time of heating in microwave is dependent on the volume and material of samples. Similar to the heating scheme of Kulshreshtha et al. (2017), 160 W for 2 minutes was followed by 700 W for 3.5 minutes for a wet mix of 177 grams. Ultimately, heating a mixture of 503 grams for 5,5 minutes at 700 W was sufficient to create a hardened CoRncrete sample of roughly 260 ml. The sample required air drying for the sides, bottom and inside to harden. Bigger volumes required increasingly long heating time at an increasingly high power. As gelatinisation rate should be optimised, this can create uncertainty for heating schemes of larger products. A sample of 260 ml already required 700 W, which was the highest power output of the Whirlpool GT288. Though the Tarrington House MWD5130 had 1000 W of power, scaling to industrial scales was deemed impossible.

The wet mix was put in the oven for 24 hours at 110 °C, as previously found by Tulip et al. (2023) as optimal. The Memmert UF75 oven included two settings next to the temperature and timer, called ‘flap’ and ‘fan’. ‘Flap’ controlled the amount of fresh air mixed into the chamber, allowing control of the moisture levels. ‘Fan’ controlled the forced circulation of air, creating a homogenous temperature and increasing the air passing the samples when increased. A fan and flap setting of 50% resulted in seemingly homogeneous gelatinisation and sufficiently extracted moisture to create hardened CoRncrete.
To reduce curing time, a rule of thumb is increasing the temperature by 10 °C and halving the oven time. OMC4, containing 0.250 - 0.500 mm sand and cornstarch, was heated for 12 hours at 110 °C. The sample had a similar appearance to the samples that were heated in the oven for 24 hours. However, the long oven time reduced the speed at which the result of new iterations could be analysed, making oven heating less favourable for this study.

A wet mix of 375 grams was poured in the silicon mould, covered with an aluminium foil ‘lid’ and heated at 120 ºC for 2 hours. As this provided a sufficiently moist mixture for further processing while no starch was visibly not gelatinised, this heating scheme was seen as sufficient. Heating two wet mixtures of 375 grams was possible in the oven, showing the scalability potential of this heating scheme and mechanism.

5.2.4 Dehydration and rehydration

After gelatinisation, the wet mix requires complete dehydration in order to control the rehydration and final forming phase.

As proposed by (Aled Roberts, 2022), separating the wet gelatinised mix into smaller sections increases the surface area ultimately accelerating the dehydration rate. Dehydration is done in the oven as the increased temperature and forced air are able to extract moisture effectively. The smaller sections are spread in an oven tray to optimise the contact surface between the mix and the air. 'Fan' and 'Flap' were increased to 100% during dehydration to improve airflow and moisture extraction. Heating a gelatinised mixture made from 375 grams of wet mix for 60 minutes at 90 °C resulted in a dehydrated gelatinised mixture. Multiple gelatinised mixtures made from 375 grams of wet mix required 90 minutes of oven dehydration at 90 °C. The size of sections of gelatinised wet mix, volume of gelatinised wet mix, oven volume and oven airflow capacity are important factors for scaling the dehydration process.

The dehydrated was crushed to a powder using a hammer. Whether the mix was dehydrated could be concluded here: If not sufficiently dehydrated, the CoRncrete particles would stick to each other with a glue-like binder, while fully dehydrated mixtures pulverised upon impact. Pulverising the mixture for three 40 by 40 mm cylindrical samples required constant impacts for 15 to 20 minutes. This manual process was energy and time intensive and the impacts caused losses in dehydrated mixture particles. Additionally, the resulted gelatinised dry mixture contained a variety of particles sizes. This process was the least refined of this manufacturing process and should be the initial focus of optimisation with specialised equipment.

The gelatinised dry mix requires rehydration before final forming in the hydraulic press. As optimised by Aled Roberts (2022), 95% gelatinised of dry mix was rehydrated with 5% water. Rehydration of the gelatinised dry mix produced a distinctive smell, comparable to that of wet asphalt after summer rain. Rehydrated mix looks like moist sand with a lot of air inside. To reduce the mix from air drying, a lit was kept on the rehydrated mixture during final forming.

Figure 39: Smaller sections of gelatinised mixture

Figure 40: Crushed, dehydrated gelatinised mixture

5.2.5 Hydraulic press shaping

The pressure in the Carver Heat Press is controlled manually by cranking a shaft. This causes the accuracy of the pressure to be limited. Additionally, the gauge measured in steps of 0.5 metric tonnes, making it impossible to read 2.83 metric tonnes (Figure 41). As the pressure was never increased above 3 metric tonnes, it is believed the pressure was applied with an accuracy of ±0.15 metric tonnes.

Due to the air in the rehydrated mixture, initial layers were best compressed by hand. This reduced the number of compression cycles necessary for final forming of a sample, saving time. Initial two to four compressions were performed with the long piston as the pressure caused a lot of deformation. When the mould started to fill up, the final one or two compressions were performed with the small piston.

As found by Roberts & Scrutton (2023), 22 MPa of pressure was used to compress the CoRncrete. As the Carver Heat Press measures force in metric tonnes, 2.83 metric tonnes provided 22 MPa of pressure on the 40 mm top surface of the samples. In reality, a force between 2.70 and 2.95 was likely applied.

Due to the height of the opening of the press, samples with a maximum height of 40 mm height could be manufactured. However, five to six compression cycles were necessary and demoulding required five cycles. A hydraulic press with a higher opening and more accurate or computer controlled pressure could improve the final forming process. Ideally, the mould is at least twice as high as the sample, reducing the number of times the mould needs to be filled with the rehydrated mixture. Additionally, a two part mould could reduce the demoulding time.

Due to the hardness of sand, compressing the rehydrated mix caused scratches in the inner wall of the cylindrical chamber and indentations in the pistons. The aluminium powder caused by the scratches on the cylindrical chamber gave samples a grey gradient on the curved surface of the cylinders. These damages might reduce the quality of the samples produced with the mould over time.

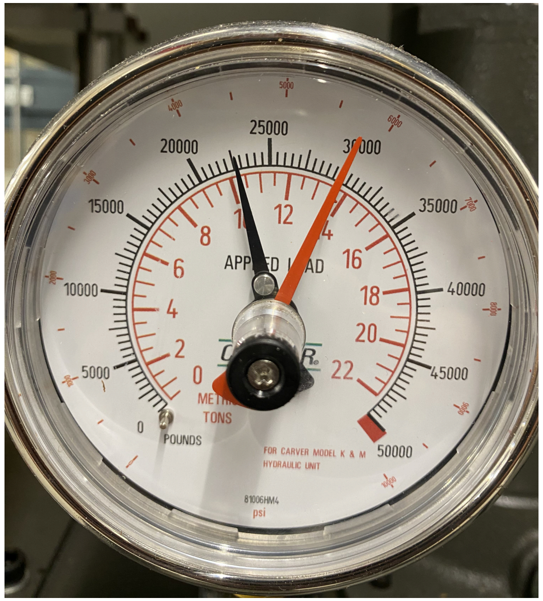


Figure 41: Hydraulic press pressure gauge

5.2.6 Pigmentation

MFC1 contained 3 drops each of blue and yellow food colouring with the goal of creating green. Comparing MFC1 to samples with Fine sand made in the hydraulic press (Figure 42) shows a significant greener colour in MFC1. The concentrated food colouring was added to the wet mix rather than being diluted in the water content and then added to the dry mix, causing heterogeneous colouring (Figure 42). Next to adding pigmentation, changing the appearance of CoRncrete through addition of different types of sand should also be further researched. OMC5 differed in colour compared to other oven samples (Figure 43). OMC5 contained a different batch of medium sand retrieved from the Microlab.

Figure 42: Sample containing Fine sand without pigmentation (left) and with pigmentation (right)

Figure 43: OMC samples containing different batches of the same sand grain size

Figure 44: Desirable pavement colours: heather violet (left) (Slimbestraten.nl, n.d.), red and yellow (middle) (VSB Sierbestrating, n.d.), and dark grey (right) (Snoei Tuinmaterialen Bleiswijk BV, n.d.)

The colour requirements set by municipalities can be met using this pigmentation method. The interviewed municipality had 'Heidepaars' (heather violet) (Figure 44) as a required colour. Additionally, shades of red, yellow and grey are conventional in pavement (Figure 44).

Pigmentation should be diluted in the water content of CoRncrete for homogeneous pigmentation of samples. As pigments should be mixed with the water content of the wet mix, this might influence the gelatinisation process of coloured CoRncrete. As more variables increase the complexity of this study. Due to time constraints, colouring CoRncrete was seen as an unnecessary additional variable, and is therefore not further researched in this study.

5.2.7 Post-processing

For material testing to understand mechanical properties, symmetrical shapes are required. An attempt at haping the microwave manufactured 'cupcakes' into symmetrical cylindrical shapes was done using a belt sander, resulting in Figure 45-left. Though the shape changed, the sandpaper from the belt sander was turned dull, most likely due to the hardness of sandpaper and the sand in the sample. Hardness is a material property that measures a substance's resistance to deformation, indentation, or scratching (Shane, 2025). Most likely, both materials exhibit a comparable hardness, causing deformation, and scratching in both the sandpaper and the CoRncrete sample.

Additionally, after sanding the severed top surface of OMC1, the cylinder was cut through the middle to produce two smaller cylinders for additional compressive testing (Figure 45). An electrical sanding belt and a hacksaw were used. Similar to the microwave samples, both tools became dull in the process while deforming the CoRncrete samples.

Post-processing is likely possible with 'diamond' tools, used for cutting e.g., sandstone, granite and concrete (Z-lion, 2023; Richoice, n.d.). However, since diamond tools are expensive and not available at the current manufacturing facilities, post-processing should be avoided as. Forming the final concept and other CoRncrete products should not require post-processing.

Figure 45: Post-processing CoRncrete with the belt sander (left) and hacksaw (right)

5.3 Samples

Appendix D explains the manufacturing process and material composition of all 43 CoRncrete samples made during the tinkering phase. In total 9 samples were manufactured in the microwave (Figure 46), of which 8 in the residential kitchen and one in the Materials Lab. A total of five samples were manufactured in the convection oven in the Materials Lab (Figure 47). 29 samples were made using the oven and hydraulic press, 11 containing cornstarch (Figure 48) and 18 containing potato starch (Figure 49).

Figure 47: Oven samples

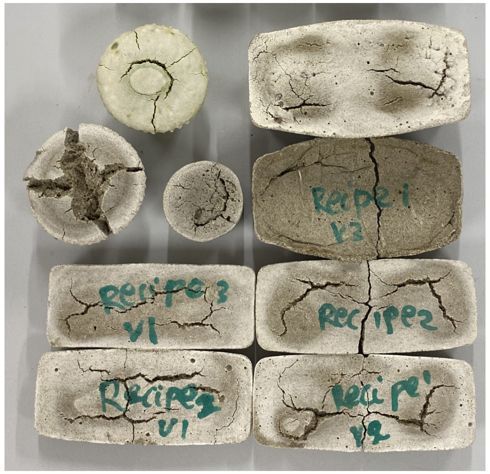


Figure 46: Samples made in the microwave

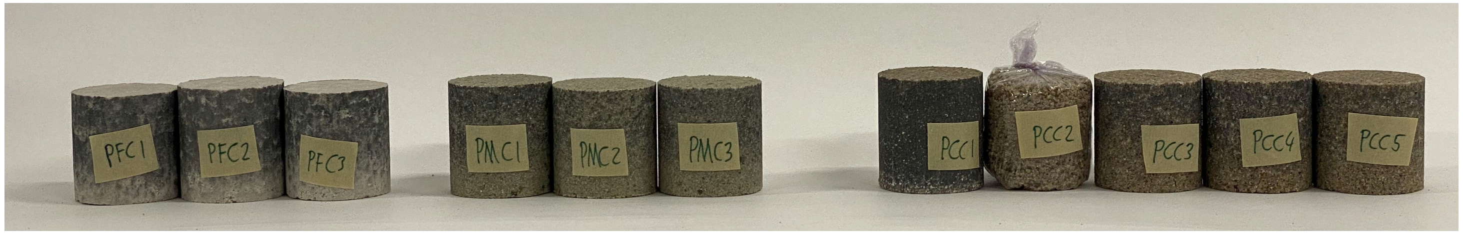


Figure 48: Oven and hydraulic press samples containing cornstarch

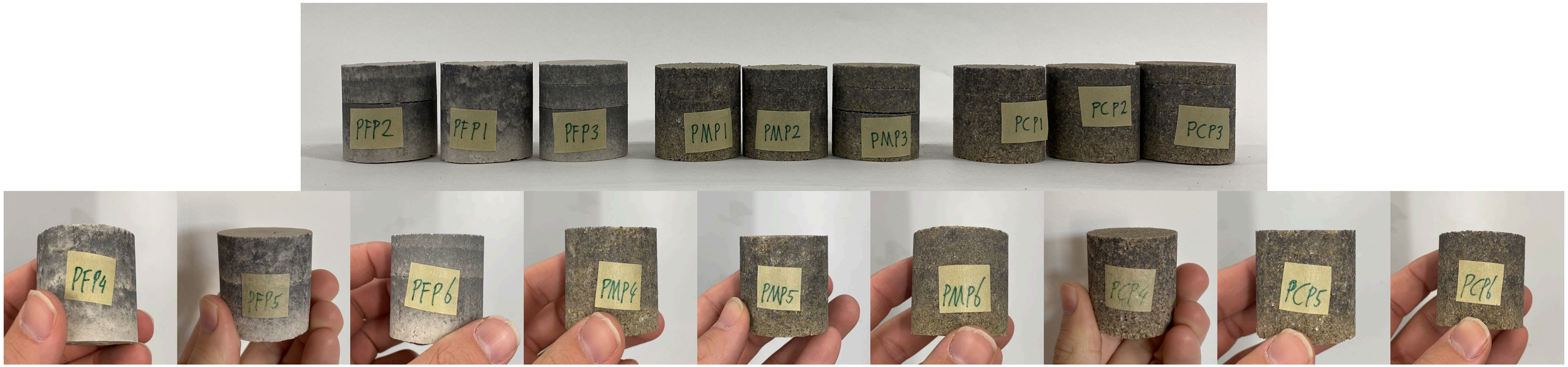


Figure 49: Oven and hydraulic press samples containing potato starch

5.4 Evaluating samples

5.4.1 Quality and Scalability

Manufacturing process

From tinkering could be concluded that the microwave produces CoRncrete with large deformations (Figure 50). A microwave uses electromagnetic waves that are absorbed by the water molecules in the wet mix (Whirlpool, 2020). The temperature increases from the inside towards the outside (Whirlpool, 2020). This has the benefit that the inside evaporates moisture and hardens before the outside does. However, the deformation might also be accounted to this characteristic of the microwave. Presumably, the escaping water vapor moves the mixture out of the way, creating holes and pushing the top layer up.

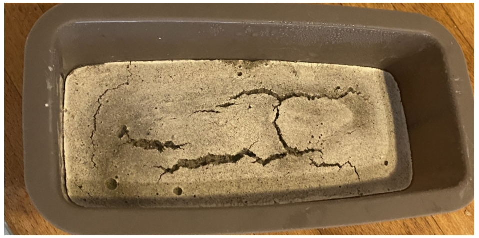


Figure 50: Sample made in the microwave with visible deformations

The samples made in the oven released easily from their mould. All samples came out of the oven completely dried and featured a reflective film on some parts (Figure 51). All samples showed smaller cracks on the curved surface of the cylinder and deficiencies on the top surface (Figure 51), while the bottom surface was smooth. The holes in the mould created small dots of hardened CoRncrete on the top of the samples (Figure 51).

Figure 51: Deficiencies of oven samples

Oven manufacturing produced higher quality samples than the microwave, likely attributed to the mould design. Additionally, the oven heats the material through heat transfer with the air in the oven, making the temperature increase less instantaneous (Maytag, 2023). However, slow heating combined with forced air absorbs moisture from the samples (Maytag, 2023), likely drying out samples, creating cracked surfaces. Cracks in the samples likely reduce the compressive and water resistance of the samples as the cavities contain air rather than CoRncrete. Cracks might be minimised by increasing the water content in the wet mix.

The first two samples were made with the wrong pressure as the calculation from 22 MPa to metric tonnes was not known. The first sample was loaded with roughly 12,5 metric tonnes which is approximately 4,5 times too much pressure. The curved surface of the cylinder is increasingly dark, compared to other samples formed in the hydraulic press (Figure 52). Consequently, PCC2 was made from the left-over material of PCC1 (Figure 52). This time, the sample was compressed with 1 metric ton. Too little pressure caused the sand to crumble easily, showing a lack of bonding.

Figure 52: PCC1 made with too much pressure (left) and PCC2 made with too little pressure (right)

PCC3 and PCC4 and all samples from that point on were compressed with a load of 2.83 (±0.15) metric tonnes. The produced samples had a high-quality finish, with little imperfections in the surfaces and sharp edges, following the shape of the mould (Figure 53).

Figure 53: PCC3 (left) and PCC4 (right)

Samples of the highest quality are formed in the hydraulic press, when comparing to the oven and the microwave. Except for cracks appearing due to a faulty hydraulic press protocol, CoRncrete shaped in the hydraulic press contains no cavities and minimum imperfections. This will most likely improve the compressive behaviour and promote perceived trust in CoRncrete as a GP material.

Due to the compactness of the material, it will likely be perceived as stronger than the oven samples. Medium sand creates the most high-quality CoRncrete, but technical data should support the technical feasibility. Addionally, technical data should highlight the difference between potato starch and cornstarch-containing samples as non were visible.

Cracks

Manufacturing the first 11 samples, up to and including PCC5, in the hydraulic press, no clear protocol for the hydraulic press was performed. Conversely, on the 6th of January, setting up a protocol was attempted (Table 7). The goal of the protocol was to let air escape for each compressed layer, creating a more evenly compacted material and to improve the consistency of sample manufacturing.

Step	Action
1	Rehydrate the gelatinised dry mix and mix thoroughly
2	Fill the mould with rehydrated mix
3	Compress with fingers
4	Fill the mould with rehydrated mix
5	Compress with fingers
6	Compress with long piston at ±2.83 tonnes
7	Increase pressure to ±2.83 tonnes if it drops
8	When it stops dropping quickly, leave it for 3 to 5 minutes
9	Repeat step 1 to 7 once or twice
10	Fill the mould with rehydrated mix
11	Compress with fingers
12	Compress with small piston to ±2.83 tonnes
13	Repeat step 9 to 11 until the small piston fits snug onto the chamber at 2.83 tonnes. Leave for 15 minutes, keeping force at 2.83 tonnes

Table 7: Hydraulic press protocol of 6 January 2025.

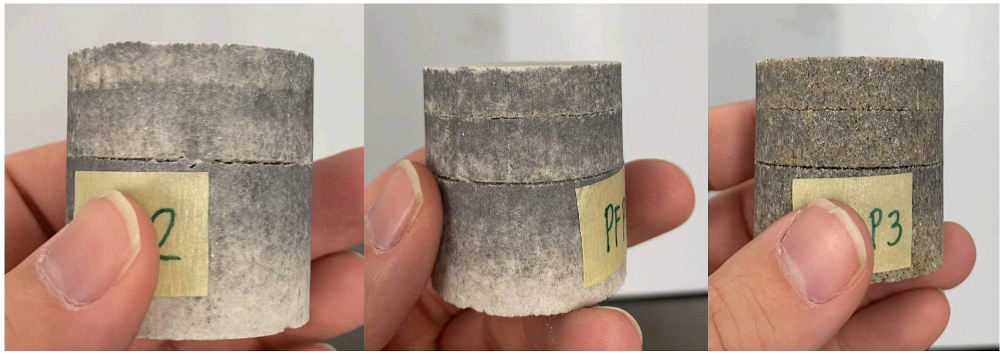


Figure 54: Samples with cracks due to hydraulic press protocol

Out of the nine samples produced on January 6th, five samples ended up containing horizontal cracks (Figure 54). Most likely this can be attributed to each layer within the sample starting the drying process after being compressed for longer periods. This likely has negative effects on the mechanical properties of the samples while the perception of the material is likely to be more fragile. Therefore, more samples were manufactured to improve the manufacturing protocol while simultaneously providing more samples for the technical analysis to research the effects of cracks.

Having no protocol worked better than the protocol. The main difference is the waiting time between pressurising the samples. Before the protocol, the mould was filled without giving the different layers time to start drying. The rehydrated mixture is should be covered with a lid and remixed before filling the mould to ensure homogeneous moisture across the mix. The improved protocol can be seen in Table 8.

Step	Action
1	Rehydrate the gelatinised dry mix and mix thoroughly
2	Put the lid on the rehydrated mix container
3	Take the lid off the rehydrated mix container
4	Mix the rehydrated mix
5	Fill the mould with rehydrated mix
6	Compress with fingers
7	Put the lid on the rehydrated mix container
8	Compress with long piston at 2 tonnes
9	Repeat step 2 to 7 once or twice
10	When the sample can be pressed with the small piston, repeat steps 2 to 6, then compress with the small piston at 2 tonnes
11	Repeat step 9 if the small piston inserts completely without reaching 2,8 tonnes
12	Compress with small piston to at least 2.83 tonnes
13	Take the sample out

Table 8: Impoved hydraulic press protocol.

Starch

Two samples using the cupcake-mould were made in microwave to compare tapioca starch with cornstarch. The sample containing tapioca starch had significantly bigger deformations than the 'cupcake' containing cornstarch (Figure 55). This provided a visual insight of what Roberts & Scrutton (2023) described as "complex multi-factor interactions" of starch gelatinisation. Each starch type will most likely have its own ideal sand grain size, heating scheme and water content. To optimise the manufacturing process, a focus on less variable is desirable in this study. This research focused on cornstarch and potato starch as they were used by current research.

Figure 55: CoRncrete cupcakes containing cornstarch (left) and tapioca starch (right)

Sand

The medium and coarse sand, measuring and 0.250 - 0.500 and 0.500 - 1.000 mm, respectively, produced a homogeneous wet mix and rehydrated mix. However, the fine sand, measuring 0.125 - 0.250 mm, contained concentrations of moisture when water was added. This increased mixing times and likely caused impurities in the samples containing fine sand. Additionally, this could negatively affect gelatinisation through insufficient water in one part of the sample and excessive water in another.

The medium and coarse sand created a pourable wet mix, while wet mixes containing fine sand showed less liquid behaviour, increasing the effort and time necessary for evenly filling moulds. This could pose problems in larger moulds when scaling manufacturing in the oven and microwave.

The medium sand created a marginally more pourable mix compared to the coarse sand. Additionally, medium sand created a smoother, more compact finished product,

Samples containing fine sand showed slightly more imperfections on the top and bottom surface, while medium sand created slightly smoother, more tightly compressed samples compared to the coarse sand. This makes medium sand the most ideal sand grain size for manufacturing CoRncrete on a lab scale. These qualities will likely translate to a more accurate scaled manufacturing process.

Mould

Attempting to reduce the deformation of samples in the microwave, a surcharge of 2 kilograms was added on top of the sample. However, this created different deformations as the supple silicon mould was not able to hold its shape under the weight. Additionally, the sample could not release its moisture sufficiently, creating a bendable, moist sample.

Mansour et al. (2020) proposed a Teflon mould with a bolt-and-nut connected top-layer to improve the finish quality of CoRncrete manufactured in the microwave (Figure 56). Adding holes for evaporation will likely reduce the time needed for hardening. The amount, size and placement of these holes should be researched.

Figure 56: An improved mould for microwave CoRncrete manufacturing (Mansour et al., 2020)

The oven mould allowed water to leave the wet mix with water collecting around the edge between the plates and cylinder, and escaping from the holes during filling (Figure 57). Since prevention was not possible, the mould was cleaned of excess moisture by wiping it with a cloth. The remaining moisture was viewed as accepTable. Additionally, the mould can be improved to reduce the cracks in samples manufactured in the oven. Most likely, the current amount and size of the holes was too large, allowing too much moisture to escape, drying out the sample.

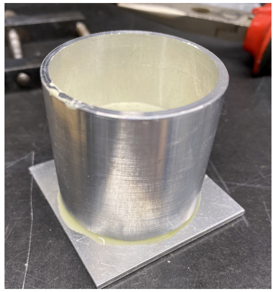


Figure 57: Moisture escaping from the wet mix when filling the mould

To make the hydraulic press mould more durable for scalable manufacturing, a steel alloys with an increased hardness should be used. As the press mould became increasingly rough from manufacturing 26 samples, polishing with P1500 sandpaper was necessary to allow smooth insertion and removal of the pistons.

5.4.2 CoRncrete sustainability

Manufacturing CoRncrete in the oven requires heating the material for 24 hours at 110 °C. The Memmert UF75 has a maximum temperature of 300 °C and a maximum electrical load of 2500 W (Memmert GmbH, 2025). 110 °C is roughly 36,67% of the maximum output, roughly equalling 916,67 W. Running for 24 hours at this wattage equals 22 kWh. Comparing this to microwave manufacturing, that uses 700 W for 5,5 minutes, amounting to 64,17 Wh. It should be noted that the oven had sufficient space for about 20 samples at the same time. Assuming this, the energy per sample would amount to 1,1 kWh, requiring 94,17% more energy than the microwave. Researching the effect of heating in the oven for 12 hours at 120 °C could improve the sustainability of oven manufacturing.

Oven heating for gelatinisation requires heating for 2 hours at 120 °C. 120 °C is 40% of the maximum output of the Memmert UF75, equalling 1000 W for 2 hours. This amounts to a total of 2 kWh. Preparing a mixture for six samples was done during tinkering, but this could likely be increased to at least 10 samples. This results in 0.2 kWh for gelatinisation. Dehydration increased from 60 to 90 minutes at 90 °C when dehydrating six in stead of three samples. Following this trend, drying 10 samples would take roughly 135 minutes. 90 oC is 30% of the maximum output, requiring 750 W for 135 minutes or 2.25 hours. In total roughly 1.69 kWh is required for all samples, or 0.169 kWh per sample. In total 0.369 kWh is required for gelatinisation and dehydration. On top of that, energy is required for hydraulic press forming, but this is negligible due to the low pressure requirement of 22 MPa (ChatGPT estimated an energy consumption of 0.00044 kWh).

Potatoes are abundantly farmed in the Netherlands. Utilising potato starch allows a direct collaboration with potato farmers, improving sustainability and enhancing the desirability of CoRncrete for Municipalities.

5.5 Conclusion

CoRncrete can best be manufactured in the hydraulic press due to the expected superior compressive strength and the compressive strength potential shown in current research (Roberts & Scrutton, 2023). The samples formed in the hydraulic press contained no deformations, creating a high quality material that is likely perceived as strong and trustworthy as a construction material. Gelatinisation in the oven allows for large volumes, while grinding, and compression forming can be done at large volumes and high speeds at industrial scales.

Manufacturing in the oven and hydraulic press is more energy efficient than oven manufacturing. Lastly, manufacturing in the oven and hydraulic press takes a total of roughly 4 hours for three cylindrical samples. This allows for quick prototyping, while simultaneously accelerating scaled manufacturing.

Pigmentation is possible through addition of pigments or sand with desired colours in the gelatinisation phase, while post-processing should be avoided due to the need for expensive equipment.

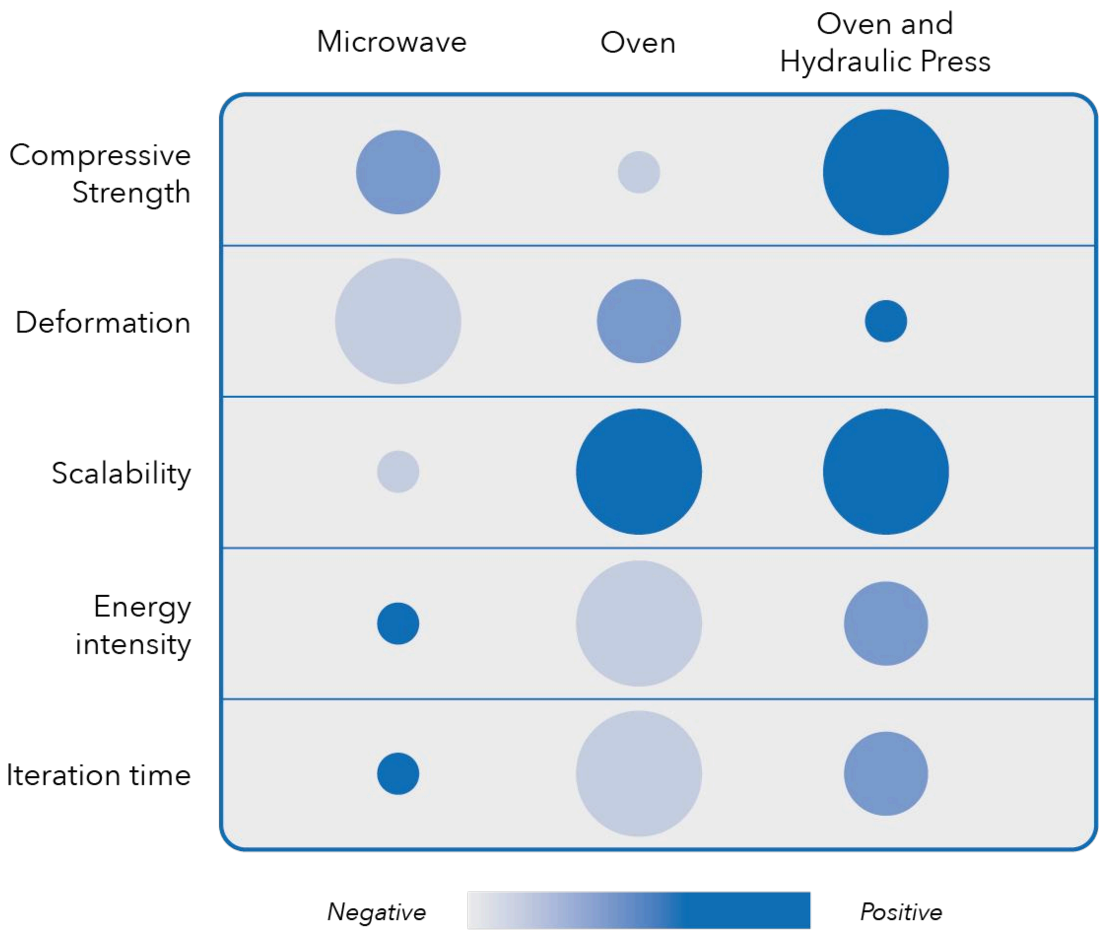


Figure 58: Comparison of CoRncrete manufacturing techniques

Limitations

Limited access to capable testing equipment as available during this study. This caused the decision-making during tinkering to be based on observations rather than data.

Reflection

In hindsight, I could have known the 10kN load cell would never be enough to test the current samples of CoRncrete on their compressive behaviour. 10 kN equals 7,96 MPa on the samples with a 40 mm diameter top surface, while all previous research found UCSs above 13,70 MPa (Kulshreshtha et al., 2017; Mansour et al., 2020; Tulip et al., 2023; Roberts & Scrutton, 2023).

Focusing on forming CoRncrete in the hydraulic press would have allowed for more in depth material composition tinkering.

Future Research

As the microwave is the most energy efficient manufacturing process and allows for rapid prototyping and production, future opportunities where microwave manufacturing is optimal should be identified. While only performing the gelatinisation phase in the oven improves sustainability, future research should identify the challenges and benefits of performing the gelatinisation in the microwave. Scalability will likely be the most prominent challenge.

experiential characterisation

How do users perceive CoRncrete?
What actions do users perform with CoRncrete?
How does touching CoRncrete feel?
What emotions does CoRncrete elicit?
What meaning(s) do users connect to CoRncrete?
How do different sand grain sizes affect the perception of CoRncrete?
Which experiential characteristics of CoRncrete does the perception explain?

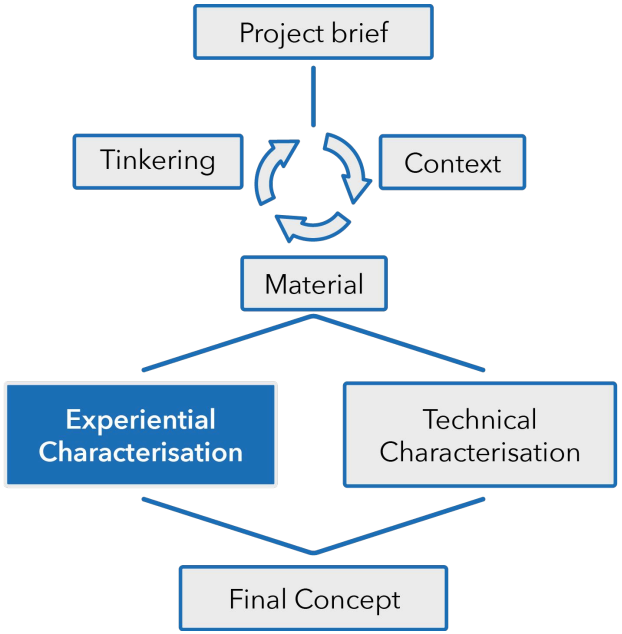


Figure 59: Experiential Characterisation section in the project structure

To design a product with a novel material, next to technical aspects, information about how the user will experience the material are crucial for the acceptation and success of the product (Camera & Karana, 2018; Karana et al., 2015). Gathering user information about a material is called 'Experiential Characterisation' (Karana et al., 2015). This chapter describes interviews aimed at understanding experiential properties of CoRncrete and the effect of different constituents. The experiential character of CoRncrete is used to design the final concept with a application and material fitting user experience.
Camera & Karana (2018) describe three research questions for experiential characterisation:

- What do people experience when they encounter the material?
- To what extent do people agree with each other?
- Why do they experience a material the way they do?

The Results section explains what people experience when they encounter the material in four categories (Figure 60). The Performative section describes what actions participants performed with a material sample (Figure 60). How CoRncrete samples are sensed is described in 'Sensorial' (Figure 60). Emotions that the samples conveyed are explained in the Affective section (Figure 60). The Interpretive section shows the meanings participants connected to the material (Figure 60).

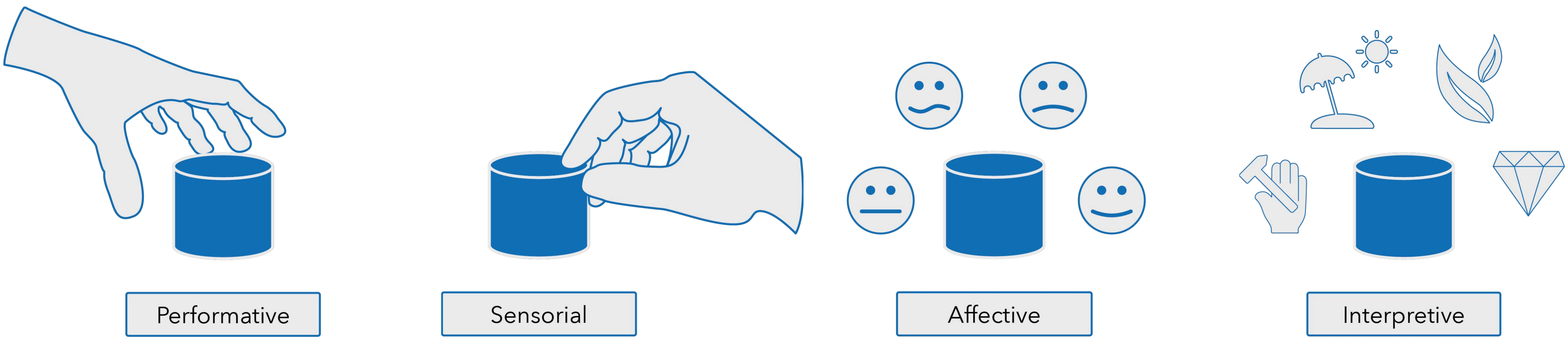


Figure 60: Four categories of user experience

6.1 Method

Using the Ma2E4 toolkit as proposed by Camera & Karana (2018) (Appendix E), eight stakeholders were interviewed, three from an architecture and construction company and five municipality employees with different function. These stakeholders were identified as crucial for implementation of CoRncrete GP through interviews, as described in section 3.1. Twice an interview was done with two stakeholders at the same time, denoted in Table 1 as duo 1 and duo 2. Four individual interviews were done. Table 9 explains the different anonymous participants.

Data was collected on the toolkit, with a video recording aiding in the analysis of the performative phase and the review of additional comments made. These videos were deleted after analyzing. Dutch vocabularies were used for the affective and interpretive section of the toolkit.

The data was analyzed using Excel. On the performative level each action could only be performed once by a participant, noting each action the participant performed. On the sensorial level each set of answers was used for calculating the average value for a sample. The data dispersion is calculated using the Standard Deviation (SD) formula in Excel (=STDEV).

Only duo two provided one set of answers, viewed as two sets of answers for calculating the average. If an emotion was named in the affective section more than once it is shown on the Figure as an area encompassing the intensity and pleasantness of each answer. The surface area does not have a direct effect on the outcome. A maximum of three emotions per participant were allowed. Both duos filled the affective section in together, providing one set of three emotions per duo. Each set of emotions was only used once for analysis, making 6 sets of emotions. All meanings given to the samples were counted on the interpretive level and presented as a graph. A maximum of three meanings per participant were given.

Three samples produced with the hydraulic press and containing different sand grain sizes were the subject of the interviews. In further reporting the word 'sample' is omitted, each sample is named after their sand size; 'Fine', 'Medium' and 'Coarse' for sand grain size 0.125 - 0.250, 0.250 – 0.500 and 0.5 – 1 mm, respectively. The samples were presented in varying order (Table 9).

The results are presented and discussed, followed by an analysis that combines the levels to identify overlapping material traits. These can be used to identify opportunities for design visions.

Participant nr.	Stakeholder type	Function	Sample order	Duo
1	Municipality	Policy maker Climate Adaptation	Coarse - Fine - Medium	1
2	Municipality	Advisor Circular Economy	Coarse - Fine - Medium	1
3	Municipality	Civil Technical Advisor	Coarse - Fine - Medium	2
4	Municipality	Ex-brick layer / Manager Pavement and Asphalt	Coarse - Fine - Medium	2
5	Municipality	Advisor Physical Living Environment	Medium - Coarse - Fine	-
6	Architecture and construction company	Architect	Fine - Medium - Coarse	-
7	Architecture and construction company	Architect	Coarse - Medium - Fine	-
8	Architecture and construction company	Project planner	Medium - Fine - Coarse	-

Table 9: Experiential participants

6.2 Results

6.2.1 Performative

Figure 61 shows how many participants performed a specific action with Fine. Holding, Caressing, Fiddling, Knocking, and Weighing were performed by multiple participants (≥3). Holding, Caressing and Fiddling were the three actions performed by most participants. 7 out of 8 participants were Holding Fine. Nine different actions were performed with Fine.

Figure 62 shows how many participants performed a specific action with Medium. Caressing, Fiddling, Holding, Knocking, Picking, Scratching, and Weighing were performed by multiple participants (≥2). Caressing, Fiddling and Holding were the three actions performed by most participants. 5 out of 8 participants Caressed Medium. Ten different actions were performed with Medium.

Figure 63 shows how many participants performed a specific action with Coarse. Holding, Caressing, Fiddling, Scratching, Weighing, and Picking were performed by multiple participants (≥2). Holding, Caressing, and Fiddling were the three actions performed by most participants. 7 out of 8 participants were Holding Coarse. Fourteen different actions were performed with Coarse.

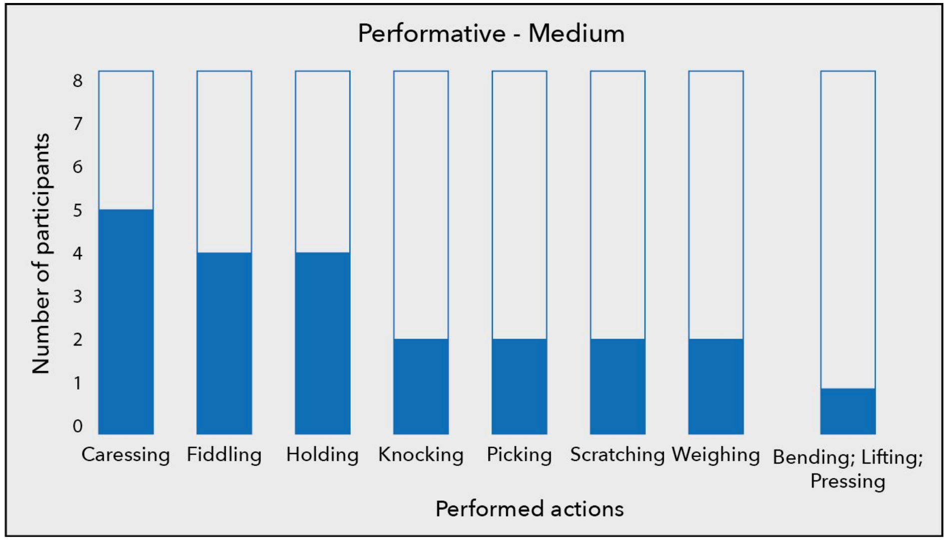


Figure 62: Performative results for Medium

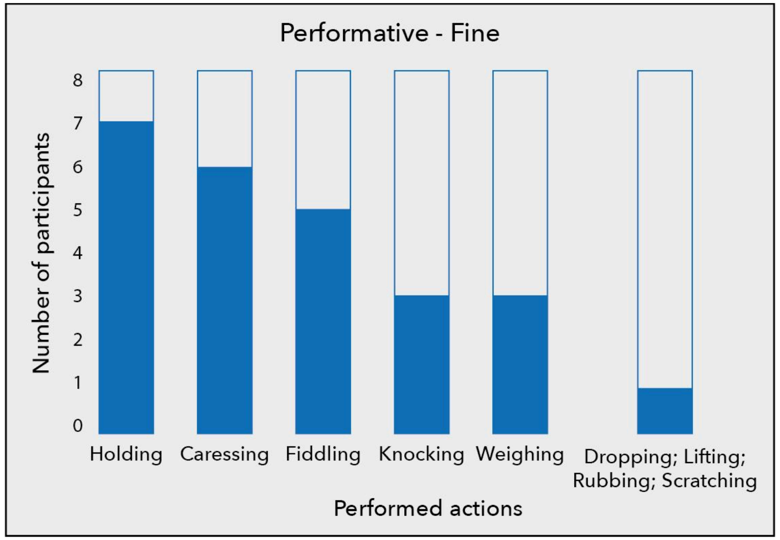


Figure 61: Performative results for Fine

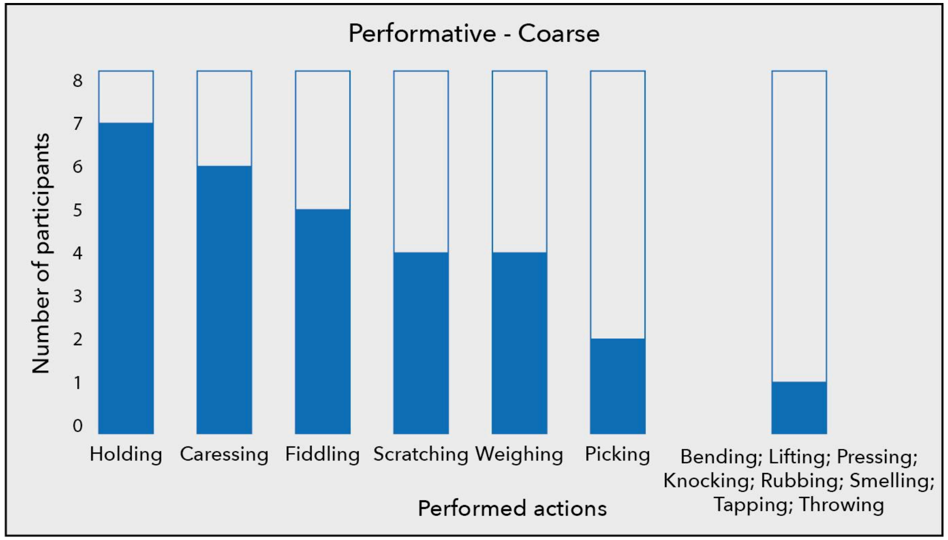


Figure 63: Performative results for Coarse

6.2.2 Sensorial

Figure 64 shows the individual sensorial answers given as small blue lines, with the thick line showing the average value for Fine. The three categories with the highest SD were Smooth/ Rough (SD = 1,20), Light/Heavy (SD = 1,19), and Matte/Glossy (SD = 1,16). Not Elastic/Elastic (SD = 0), Opaque/transparent (SD = 0), and Cold/Warm (SD = 0,71) were the three categories with the lowest SD.

Figure 65 shows the individual answers and average sensorial values for Medium. Matte/Glossy (SD = 1,36), Regular/Irregular Texture (SD = 1,30), and Not Reflective/Reflective (SD = 1,25) showed the highest SD. Opaque/Transparent (SD = 0,00), Not Elastic/Elastic (SD = 0,35), and Tough/Ductile (SD = 0,46) were the categories with the lowest SD.

Figure 66 shows the individual and average sensorial answers given for Coarse. The three categories with the highest SD were Not Reflective/Reflective (SD = 1,67), Matte/Glossy (SD = 1,41), and Cold/Warm (SD = 1,16). The three categories with the lowest SD were Opaque/ transparent (SD = 0), Not Elastic/Elastic (SD = 0,46), and Opaque/Transparent as well as Strong/ Weak (SD = 0,52 for both).

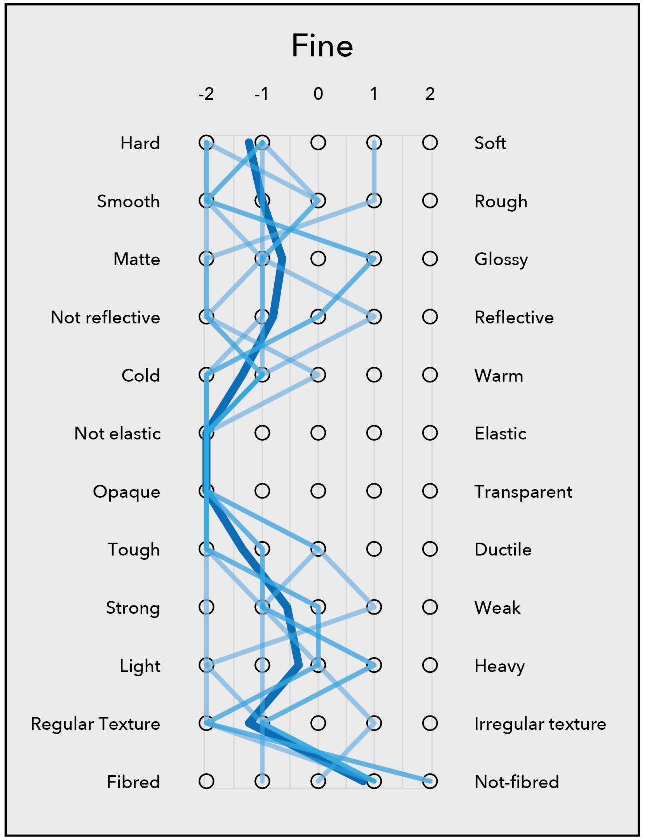


Figure 64: Sensorial results for Fine

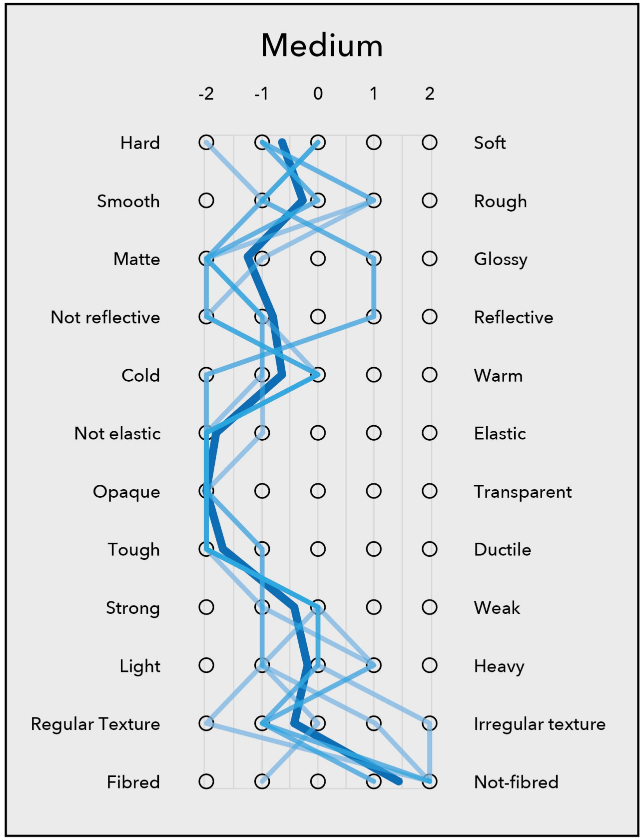


Figure 65: Sensorial results for Medium

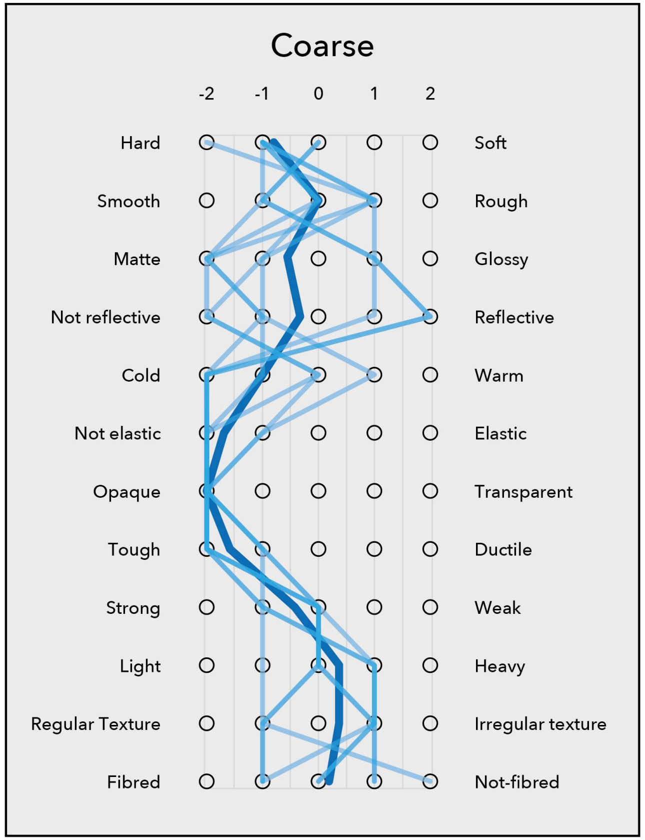


Figure 66: Sensorial results for Coarse

Fine is the hardest, while medium is the softest material. Fine is the smoothest, while coarse is the roughest material. Medium is the most matte, while Coarse is the glossiest material. Medium is the least, while Coarse is the most reflective material. Fine is the coldest, while Medium is the warmest material. Fine is the least Elastic, while Coarse is the most Elastic material. All three material are perceived as totally Opaque. Medium is the toughest, while Fine is the most Ductile material. Fine is the strongest, while Medium and Coarse are both the weakest material. Fine is the lightest, while Coarse is the heaviest material. Light has the most Regular, while Coarse has the most Irregular texture. Coarse is the most Fibred, while medium is the least Fibred.

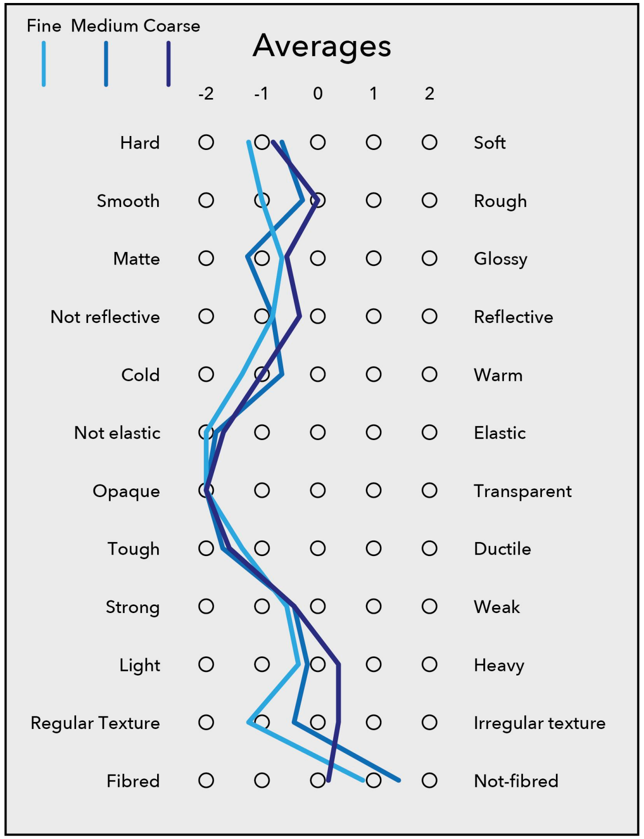


Figure 67: Average Sensorial results for Fine, Medium and Coarse

6.2.3 Affective

Figure 68 shows the emotions that Fine evokes. Four out of six sets of emotions felt Fascination. Two out of six sets felt Surprise, Attraction, Doubt, and Disgust. 66,67% of the emotions felt pleasant. Emotions for Fine were felt weak to slightly intense.

Figure 69 shows the emotions that Medium evokes. Four out of six sets of emotions felt Comfort. Three out of six sets felt Curiosity and Attraction. Two out of six sets felt Surprise. 83,33% of the emotions felt pleasant. Emotions for Medium were felt slightly intense.

Figure 70 shows the emotions that Coarse evokes. Three out of six sets of emotions felt Curiosity and Comfort. Two out of six sets felt Fascination, Attraction and Doubt. 83,33% of the emotions felt pleasant. Emotions for Coarse were felt weak to slightly intense.

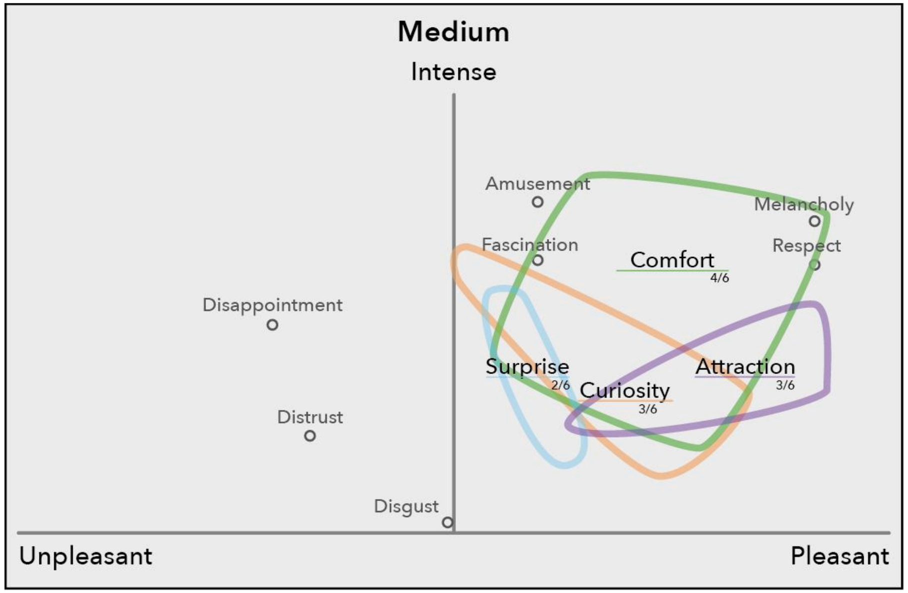


Figure 69: Affective graph for Medium

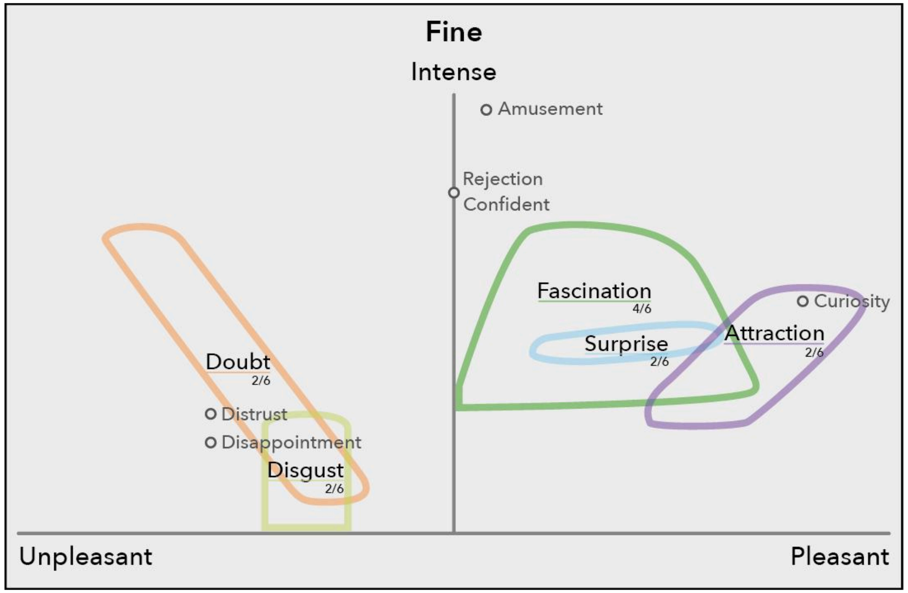


Figure 68: Affective graph for Fine

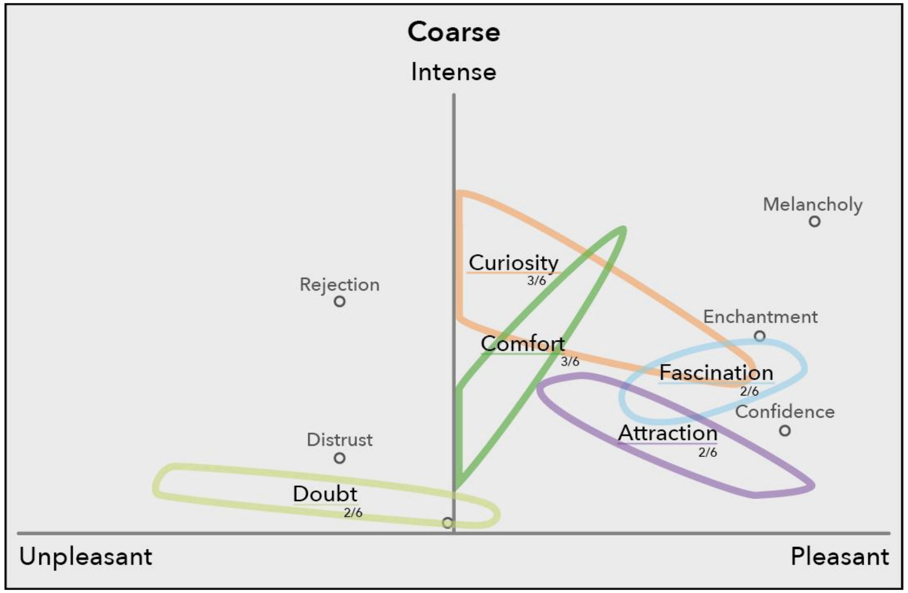


Figure 70: Affective graph for Coarse

6.2.4 Interpretive

Figure 71 shows all the meanings and how many participants connected that meaning to Fine. Twenty-one meanings, fifteen different ones, were connected to Fine. 14,29% of the meanings were Nonnatural and Manufactured. 9,52% of the meanings were Natural and Elegant.

Figure 72 shows all the meanings and how many participants connected that meaning to Medium. Twenty meanings, twelve different ones, were connected to Medium. 20,0% of the meanings were Manufactured and Ordinary. 15,0% of the meanings were Natural.

Figure 73 shows all the meanings and how many participants connected that meaning to Coarse. Twenty-two meanings, thirteen different ones, were connected to Coarse. 22,72% of the meanings were Manufactured. 13,64% of the meanings were Natural and Ordinary. 9,09% of the meanings were Sober.

While fifteen different meaning were connected to Fine, twelve and thirteen were connected to Medium and Coarse, respectively. Combining the answers of all participants, the greatest number of meanings were connected to Coarse, specifically twenty-two. Manufactured was the most frequently mentioned meaning for each sample. Additionally, all samples were mentioned to be Natural.

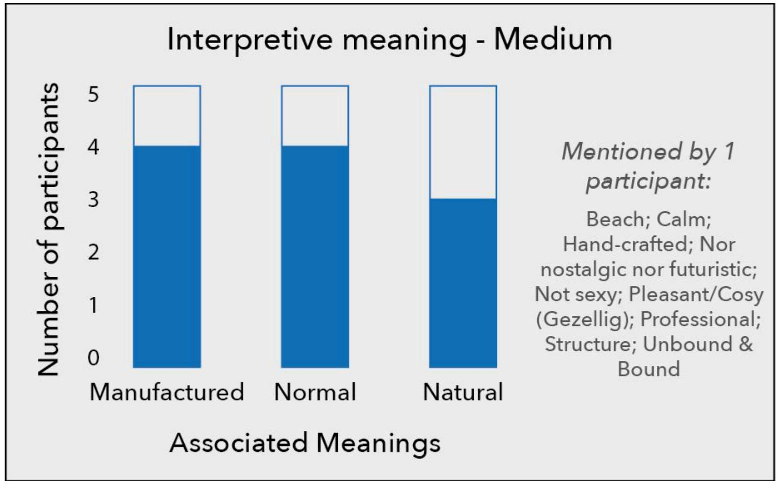


Figure 72: Meanings connected to Medium

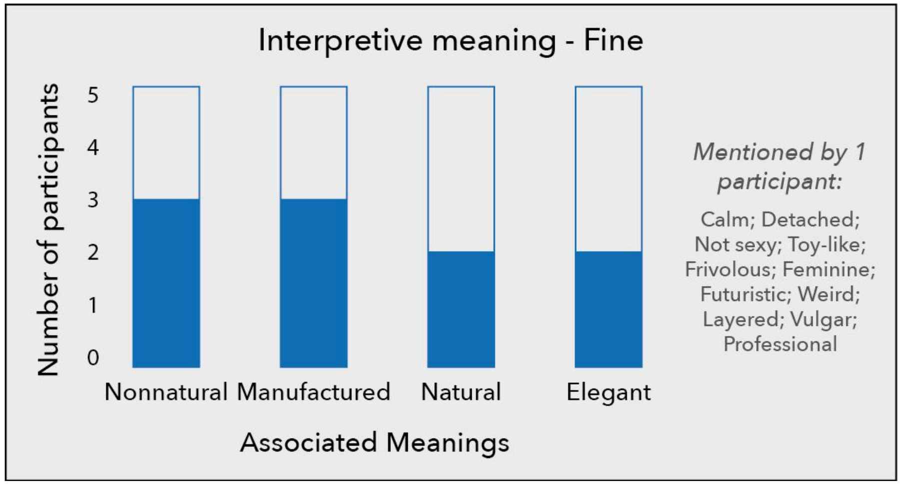


Figure 71: Meanings connected to Fine

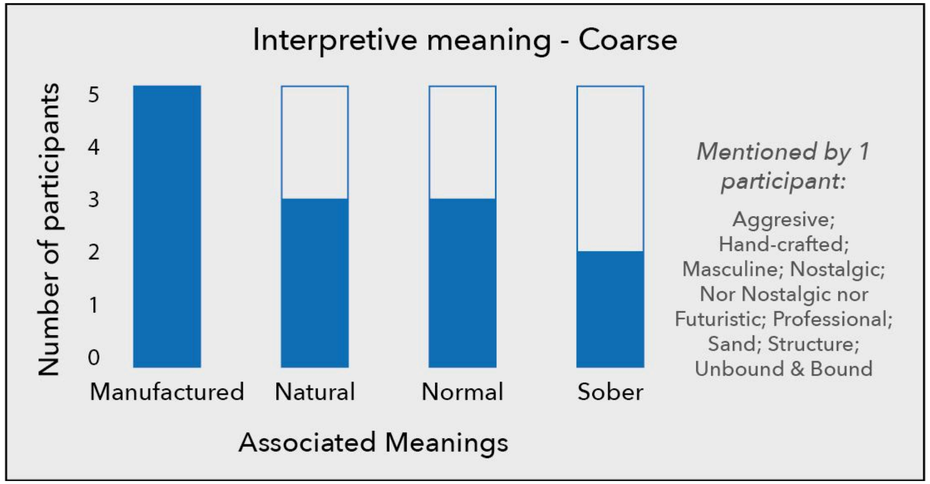


Figure 73: Meanings connected to Coarse

6.3 Synthesis & discussion

Additional quotes and remarks of the participants can be found in Appendix F, providing extra context to the relationship between the different levels of experience.

Participants generally perceived Medium and Coarse as comparable. Participant 2 questioned whether there was any difference between the two, while participant 3 said: "You are trying to fool me, this is the same as the other one". Participant 6 described Coarse as the "rougher brother" of Medium and noted that the two share similarities. These similarities likely stem from the visible sand grains present in both materials. Medium was described as resembling sand by participant 1, a leveled sand bed by participant 2, sand compressed into a solid block by participant 5, and as compressed, hardened sand and "beach in a block" by participant 6. Coarse, was similarly described as sandstone by participant 2, complemented for "a nice sand colour" by participant 3 and as looking like sand by participant 4.

In contrast, Fine was perceived as distinctly different, as no participants identified visible sand particles. Participant 2 explicitly noted that, while Medium and Coarse seemed closely related, Fine was "different", potentially due to its less familiar composition. Participant 1 and 2 together speculated the inclusion of sewage waste, while Fine was "hard to categorise" according to participant 6.

Overall, all samples were associated with concrete or minerals. Participant 5 compared Coarse to bunker concrete, while participant 6 described Fine as resembling rough marble or and participant 7 as "a rock-type composite". Participant 5 questioned whether Medium contained additional concrete, and asked "how is this different from concrete?". This shows CoRncrete has a strong perceived connection to conventional construction materials.

After learning about the material composition, participants reacted positively, appreciating the simplicity and potential environmental impact of CoRncrete. Participant 2 noted the absence of "secretly toxic" additives, while participant 3 described the simplicity of the material as "beautiful". However, participant 2 raised concerns regarding the scarcity of sand, noting that sand is actively safeguarded in the Netherlands.

Due to the hydraulic pressing process, the samples exhibited a grey gradient on the curved side of the cylinders caused by aluminium dust scratched from the mould (section 5.4). Participant 7 found the gradient dirty and disgusting, showing how this unintended surface characteristic could have negatively influenced user perception.

Beyond material perception, practical considerations for CoRncrete GP were discussed. Participant 4 explained that municipal managers often view the maintenance of GP as challenging due to the consistent presence of parked cars, hindering mowing of all vegetation continuously. Additionally, uneven growth of vegetation across a GP location results in varying maintenance needs, further complicating management. This highlights a key concern regarding the long-term feasibility of GP in high-traffic urban environments.

Regarding potential applications, participant 4 suggested that CoRncrete GP could be suitable for low-traffic infrastructure, such as access roads to small pumping stations. They also emphasised that, for CoRncrete to be viable as pavement, it would need a minimum lifespan of ten years. Participant 6 speculated the reversibility of CoRncrete's de- and rehydration process, speculating that this property could enable repairs or even bonding of multiple CoRncrete elements. They compared this potential feature to Corian, a material that can be repaired and seamlessly joined through sanding and polishing, resulting in a durable and adapTable surface (Corian® Solid Surfaces, n.d.).
An alternative application for CoRncrete was its use in 'dekvloeren' (screed floors), as suggested by participant 6. These floors serve as thermal and acoustic insulation layers in buildings (Giesberts, 2024) and require minimal waterproofing.

Lastly, participant 4 noted that bricks are often designed with chamfered edges to prevent chipping and spalling. Figure 74 shows how this design feature is applied in concrete pavement stones. Moreover, this design feature will be taken into account for the final concept design

Figure 74: A concrete pavement stone with chamfered edges (Gamma NL, 2024)

6.3.1 Fine

Figure 75 shows how the different levels of experience, explain material properties of the Fine samples.

Users were likely attracted to the smooth texture of Fine, seeing it as an elegant material. Participant 1 described Fine to be “fitting for designer kitchens”. Participant 3 would rather use it “in the garden than in the streets”. Participant 4 said the material would make a pretty gravestone or could be used in the garden. Fine looked like a rougher type of marble according to participant 6, describing the sample as majestic, chic, high-end and due to its mysterious appearance as intriguing. Participant 7 found the smoothness and the fresh or brisk colour the most pleasant qualities of the material.

Users might have been doubting if Fine would be too clean and smooth for pavement. Participant 1 found Fine too striking to be used as pavement. Participant 2 noted that the material looks clean now, but will become dirty during use, changing its appearance negatively. Participant 3 deemed the material “very slippery and very white”.

Lastly, users were potentially surprised by how lightweight but strong Fine felt, making users believe Fine was manufactured using nonnatural materials. Participant 1 described fine as a material suitable for designer kitchens without a lot of warmth or a good vibe. Participant 1 and 2 concluded together that Fine would be the least vulnerable for damages as it looks like a solid mass. Participant 6 found Fine intriguing and mysterious, speculating the components of the sample. The combination of feeling lightweight and strong while being natural made participant 8 assume it is somewhat fake or they are being confused on purpose.

Fine

Performative	Sensorial	Affective	Interpretive
Holding	Smoothest	Fascination	Nonnatural
Caressing	Coldest	Surprise	Manufactured
Fiddling	Least Elastic	Attraction	Natural
Knocking	Least Tough	Doubt	Elegant
Weighing	Strongest	Disgust	
	Lightest		
	Most regular texture		

Users are attracted to the smooth texture of Fine, seeing it as an elegant material

Users were doubting if Fine would be too clean and smooth for pavement

Users were surprised by how lightweight but strong Fine felt, making them believe it was manufactured using nonnatural materials

Figure 75: The synthesis of all 4 levels of user experience of Fine

6.3.2 Medium

The synthesis of the different levels of user experience of Medium can be seen in Figure 76. Likely, users were comforTable with in holding Medium because it looks ordinary and warm. Both participant 1 and 2 repeatedly used the adjective “gewoon” in Dutch, which translates to just or ordinary, e.g., “resembles just sand” (participant 1) and “it is just hard and rocky” (participant 2). Participant 3 called Medium “very neutral” and described it as feeling “not very innovative”. Medium “Looks very normal, not special” and “does not give you a lot of feelings” (participant 5). According to participant 8, Medium’s most unique quality was, next to very strong, that the material is “not very special” and looks “quite ordinary”.

Users might have recognised the sand grains, expected the material to be weak and soft, but due to manufacturing it felt surprisingly strong. Medium was described as resembling sand by participant 1, levelled sand bedding by participant 2, sand compressed into a solid block by participant 5, compressed, hardened sand and “beach in a block” by participant 6. Medium gave participant 2 the feeling of “playing in a sandbox”. Additionally, participant 6 explained Medium “looks more vulnerable because you visibly recognise the sand and connect that to not being strong”. However, Medium was described as “hard” (participant 2), “holds its shape well” (participant 7), and “looks very strong” (participant 8).

Additionally, users were attracted to the ordinarity and naturality, while caressing the texture and testing the toughness/softness surprised users. Medium resembled “respect for nature because it looks natural” (participant 1). Participant 6 connected Medium with the beach, a natural environment. Medium’s “natural look” was its most pleasant quality (participant 8). Additionally, participant 2 stated that Medium gave the participant “a nice feeling”. The sand in Medium was recognised, linking it to a naturally occurring material with a likely well-known tactile experience. Recognising sand grains can explain the caressing to explore the texture. Participant 2 described Medium as “hard”, participant 7 found the most unique quality that Medium “holds its shape well”, and “looks very strong” according to participant 8.

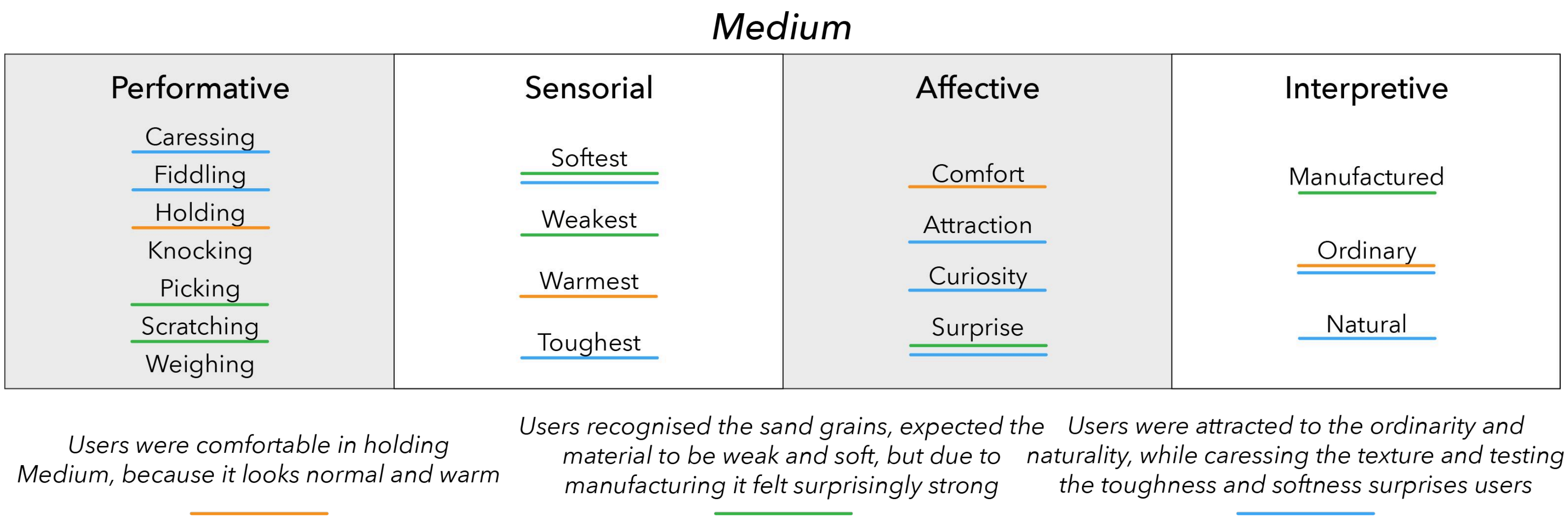


Figure 76: The synthesis of all 4 levels of user experience of Medium

6.3.3 Coarse

Figure 77 explains the experiential characteristics of Coarse, found through the different levels of user experience.

Likely, users were comforTable with holding Coarse, a heavy, sober, manufactured construction material. Participant 1 connected Coarse with a compressed flooring material. Coarse was "just a rock" and it "does not bring out a lot of emotions" (participant 2). Coarse has a close relation to concrete (participant 3 and 5) and "looks very normal" according to participant 3. Coarse looks "very normal" and "good" (participant 3 and 4), respectively. Participant 7 described the most pleasant quality of Coarse as "robust" but "a different type of robust compared to concrete".

Users were likely doubting Coarse as it seems rough and natural, but the sand seems weak enough to pick grains off. Participant 1 connected the colour of Coarse to soil and stated that "The finer the material, the less vulnerable for damages it looks because it is more one solid mass." "Maybe if I ride over it with my bike, sharp pieces come off" according to participant 2.

Participant 3 wanted to smash Coarse with a hammer to "test its strength". Participant 7 explained Coarse "looks like sand, but it is still a robust material" and expected Coarse to "fall apart, especially at the sharp edges, but it doesn't". The most disturbing quality of Coarse is that "the material is rougher and less neat", according to participant 8.

It is likely that the sand grains give Coarse an attractive, irregular, rough texture to caress and scratch, fascinating users. Participants 1, 4 and 8 found Coarse "pretty", explained by participant 8 as caused by "the different colours in the material". Participants 2 and 8 noticed dusty particles coming off the sample. Participant 2 noted that Coarse looks "like rock" or "sandstone". The material "looks organic" making the material "more accepTable", as stated by participant 2. Coarse "has a nice sand colour" according to participant 3. Participant 7 explained Coarse "looks like sand, but it is still a robust material" and expected to "fall apart, especially at the sharp edges, but it doesn't".

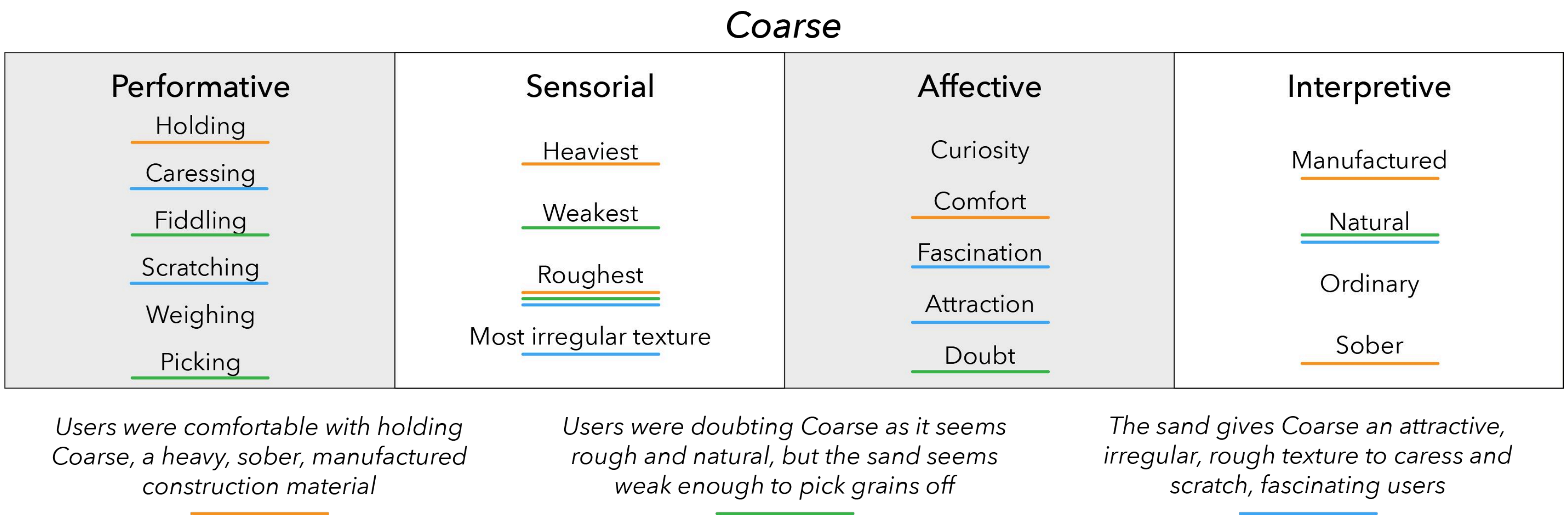


Figure 77: The synthesis of all 4 levels of user experience of Coarse

6.4 Conclusion

The visibility of sand grains in Medium and Coarse likely contributes to their recognisable, ordinary, and natural appearance. Medium and Coarse have a similar user experience, whereas Fine conveyed a more mysterious and confusing experience. While participants expected the sand grains to reduce the structural integrity, they called Medium "hard" and "very strong". Additionally, the sand provided a fascinating tactile experience, inviting curiosity and attraction.

Medium seems to have the most desirable user experience for CoRncrete Grid Pavement due to its high experienced comfort, and ordinary appearance (Figure 78). It balances novelty and recognisability, creating acceptance and trust, important features for users and architects experiencing CoRncrete Grid Pavement. Its natural appearance can improve the sustainable perception of Grid Pavement while creating a competitive advantage with concrete and plastic.

Additionally, interviews revealed a key design requirement: the final concept should have chamfered or filleted edges to prevent chipping.

Limitation

Conducting experiential characterisation interviews was unprecedented. Two samples were very alike, making the order of the samples increasingly important. Translation from Dutch to English changes some of the nuance and introduces bias by the translator. Sides of the samples contained unintended grey gradient from the aluminium hydraulic press mould. This might have influenced the user experience of the samples.

Figure 78: CoRncrete containing 0.250 - 0.500 mm sand grains

Reflection

Results of interviews were more personal with a single participant, while including multiple people facilitated open communication. Interviewing multiple people simultaneously with an individual booklet might produce the best results.

Checking multiple choice boxes on the booklet in the performative section required searching for an action while simultaneously other actions were performed by the participants. Due to the fast-moving and chaotic nature of this section, additional video analysis is recommended. Transcribing the audio can provide researchers with helpful additional insights that were not noted during the interviews.

The categories of the sensorial section are likely more difficult to understand due to the participants being Dutch and the booklet in English.

The emotional level was the most difficult section for participants, likely due to limited previous experience with connecting emotions to materials. Participant 4 joked: "I am not even emotional at home, never mind being emotional through a material."

The final reflection section of the Ma2E4 user booklet was, when correctly folded, located on the back of the sheet. This caused the section to be forgotten interviewing 6 out of 8 participants, reducing the gathered data.

Changes to the structure of the Ma2E4 user booklet are proposed, based on conducted interview experiences (Appendix G). Additionally, printing the Ma2E4 user booklet facilitated an interaction with the participants that excluded the use of screens, potentially improving open communication and the focus on physical sample exploration. Unfortunately, the booklet requires printing numerous colours on A3-sized paper.

The redesigned user booklet (Appendix G) features A4-sized paper and black-and-white printing to improve the sustainability. Using 'The world's most sustainable ink", an algae-based ink that sequesters carbon (EcoEnclose, 2022), could make this booklet CO_2 negative.

7 technical characterisation

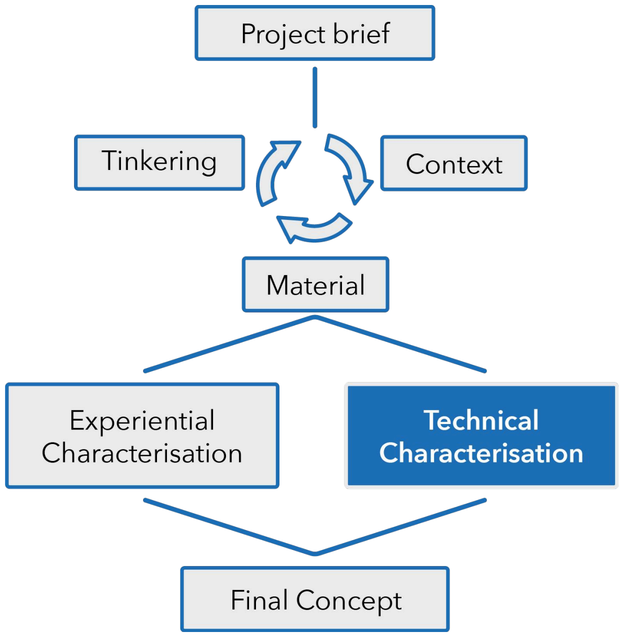


Figure 78: Technical Characterisation section in the project structure

What is the effect of components on CoRncrete's mechanical properties?
How does the hydraulic press affect CoRncrete's mechanical properties?
Which mechanical properties are relevant for the final concept design?

In the microwave and oven, 0.125 – 0.250 mm and 0.250 – 0.425 mm sand grain size, respectively, have been shown to be the optimal sand for the highest compressive resistance (Kulshreshtha et al., 2017; Tulip et al., 2023). However, for manufacturing CoRncrete using the oven and hydraulic press, as proposed by Roberts & Scrutton (2023), no optimal sand size was previously identified. Additionally, cornstarch is the binder used in most research on CoRncrete (Kulshreshtha et al., 2017; Mansour et al., 2020; Tulip et al., 2023), while Roberts & Scrutton (2023) concluded that using potato starch resulted in materials with the highest compressive resistance. Technical characterisation aims to form an understanding of the effect of material components on the mechanical properties of CoRncrete. Using the mechanical properties, CoRncrete GP's behaviour under compressive load can be predicted through modeling and future studies can make informed decisions regarding potential applications (Mardoqueu, 2023). In section 5.4, the decision was made to focus on CoRncrete manufacturing using the oven and hydraulic press instead of oven manufacturing. This section aims to support this decision with data.

7.1 Method

SLW60 according to DIN1072 bases the technical feasibility of TAWWA GreenGrids on a static, uniaxial force rather than simulating movement of vehicles through a combination of loading conditions (uniconstruct, n.d.; Spyrakos et al., 2017). Understanding the mechanical properties of CoRncrete necessary for GP design is based on this standard, performing uniaxial unconfined compressive loading on material samples.

7.1.2 Test equipment

Initial testing was done with a Zwick Z010 using a load cell of 10 kN which proved to be insufficient for the samples. Final testing was done at the Mechanical Behaviour Labs of Mechanical Engineering using a Zwick Z100 using a load cell of 100 kN (Figure 79). A loading rate of 1 mm per second is used with a start load of 0.1kN and the load stopping when the measured force drops 25% from the maximum load measured, inspired by Kulshreshtha et al.'s (2017) test setup. Displacement in mm and Force in N was measured.

Figure 80: Zwick Z100 (ZwickRoell, n.d.)

7.1.3 Data collection

The data was analysed in Excel. To calculate the Stress, the surface area of a sample is divided by the force. Strain is the measured deformation divided by a sample's height after manufacturing. Plotting the Stress against the Strain results in a curve that explains a sample's behaviour under compressive load (Figure 80). The behaviour of the curve explains mechanical properties of the material. The Young's modulus (E) explains the amount of deformation of a material caused by a force (The Efficient Engineer, 2024). The slope coefficient of the linear section or elastic region of the Stress – Strain curve represents E (Figure 80; The Efficient Engineer, 2024). The Yield Strength (YS) describes the amount of stress where the deformation of a material becomes permanent, called plastic deformation (The Efficient Engineer, 2023). The YS of a material can be found by plotting a line with slope coefficient E, moving this line by 0.2% on the Strain axis and finding the point of intersection of both lines (Figure 80; The Efficient Engineer, 2023). The Ultimate Compressive Strength (UCS) is the maximum stress value a material can withstand before failure (The Efficient Engineer, 2023). The UCS is the highest point on the Stress axis in the Stress – Strain curve (Figure 80; The Efficient Engineer, 2023). Calculating the mean mechanical properties of samples with identical compositions concludes mechanical properties of CoRncrete with certain compositions. The standard deviation shows the amount of data dispersion compared to the mean.

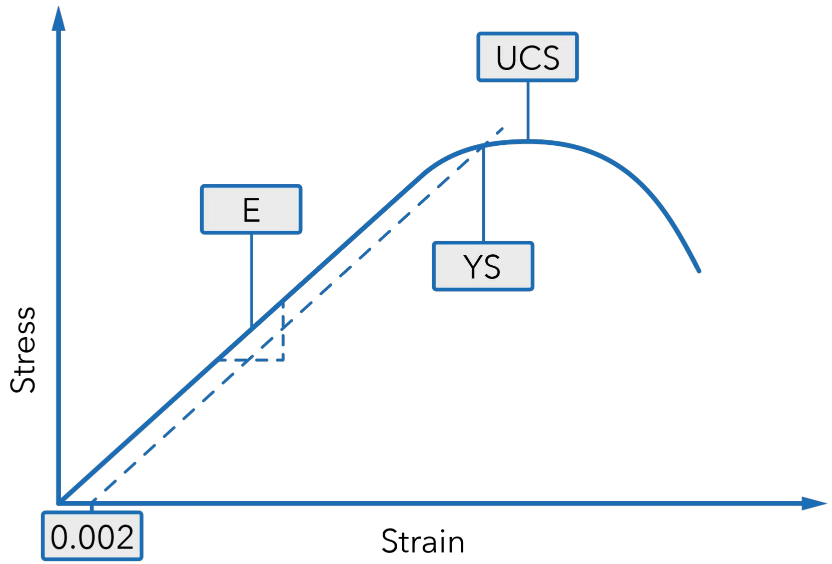


Figure 80: The Young's modulus, Yield Strength, Ultimate Compressive Strength in a Stress-Strain curve

7.1.1 Samples

To understand the relation between the different constituents of CoRncrete manufactured in the hydraulic press, a design of experiment (DOE) is prepared (Table 10). Table 11 describes the DOE to compare hydraulic press with oven manufacturing.

Factors	Levels	Level Names
Sand grain size	3	0.125 - 0.250 mm 0.250 - 0.500 mm 0.500 - 1,000 mm
Starch type	2	Potato starch Cornstarch
Manufacturing	1	Oven and hydraulic press

Table 10: DOE of hydraulic press samples

Factors	Levels	Level Names
Sand grain size	1	0.250 - 0.500 mm
Starch type	1	Cornstarch
Manufacturing	2	Oven Oven and hydraulic press

Table 11: DOE of manufacturing in the oven and in the hydraulic press samples

Samples were manufactured in the oven and in the hydraulic press as described in section 5.2. The 40 × 40 mm (H × D) dimensions were based on Mansour et al. (2020), while a cylindrical shape was chosen for its uniform stress distribution (Mardoqueu, 2023).

Initially, three samples per material composition were manufactured. However, due to the formation of cracks (see section 5.4), the number of samples was increased to five per sand grain size containing potato starch. One set of oven samples with the same composition as a set of hydraulic press samples was produced to assess the impact of hydraulic press shaping

Each sample is abbreviated by three letters and one number according to their constituents, as described in section 5.1.2. The first letter being a 'P' denotes the material is made in the hydraulic press, an 'O' denotes only the oven is used. The second letter denotes the sand grain size with 0.125 – 0.250, 0.250 – 0.500 and 0.500 – 1.000 mm abbreviated by F (fine), M (medium) and C (coarse), respectively. The number denotes the order of sample manufacturing. For example, PFP2 refers to a hydraulic press sample with fine sand and potato starch, and it was the second sample of this type.

The diameter and height of each sample after manufacturing were determined (Table 12). Three points were measured, with values averaged, to account for variations and deformations.

Sample	Initial Diameter (mm)	Initial Height (mm)	Test Nr.
PFP1	39.64	43.45	5
PFP2	39.55	42.81	4
PFP3	39.58	43.53	3
PFP4	39.72	42.63	2
PFP6	39.57	43.80	1
PMP2	39.79	41.24	6
PMP3	39.72	42.59	7
PMP4	39.86	42.37	8
PMP5	39.84	42.35	9
PMP6	39.74	42.00	10
PCP1	39.81	41.94	11
PCP2	39.83	42.45	12
PCP3	39.86	43/63	13
PCP5	39.85	42.24	14
PCP6	39.82	41.86	15
PFC1	39.70	41.54	19
PFC2	39.71	43.29	20
PFC3	39.61	41.32	21
PMC1	39.82	42.71	16
PMC2	39.81	41.32	17
PMC3	39.81	41.77	18
PCC3	39.85	41.67	22
PCC4	39.85	41.74	23
PCC5	39.83	41.21	24
OMC2	39.64	39.66	25
OMC3	39.84	40.29	26
OMC5	39.80	40.12	27

Table 12: DOE of manufacturing in the oven and in the hydraulic press samples

7.2 Results

From the displacement and force the Stress and Strain are calculated using the initial diameter and height of each sample (Table 12). Plotting the Stress versus Strain produced the curves of Figure 81 for potato starch-containing samples and Figure 82 for cornstarch-containing samples.

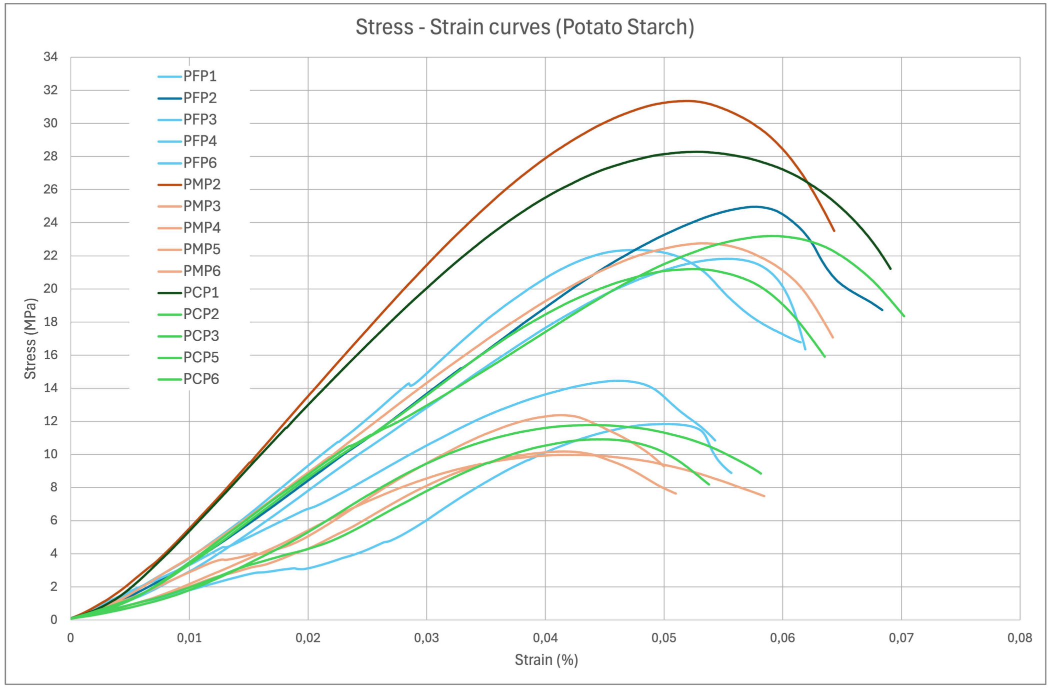


Figure 81: Stress-Strain curves of all potato starch-containing hydraulic press samples

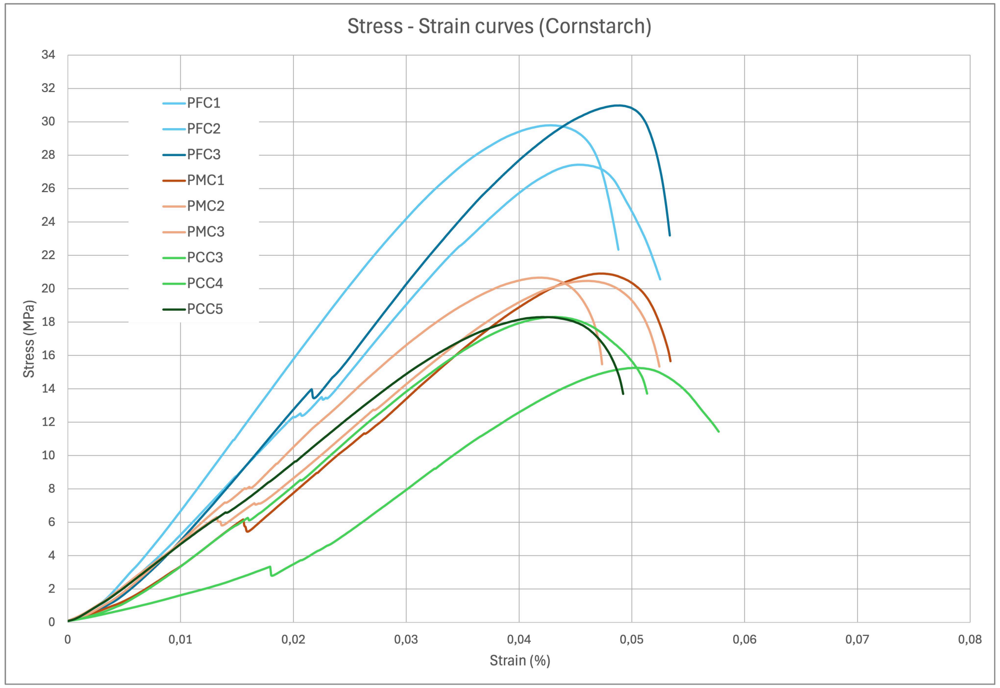
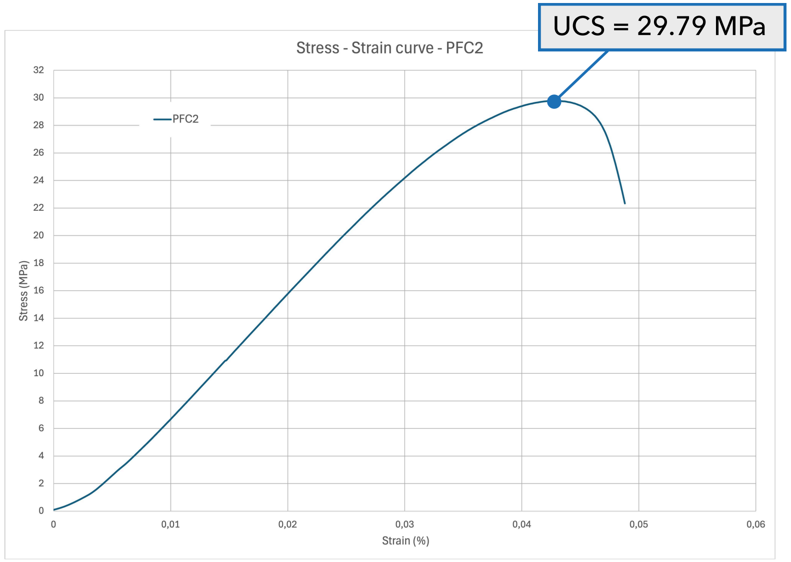
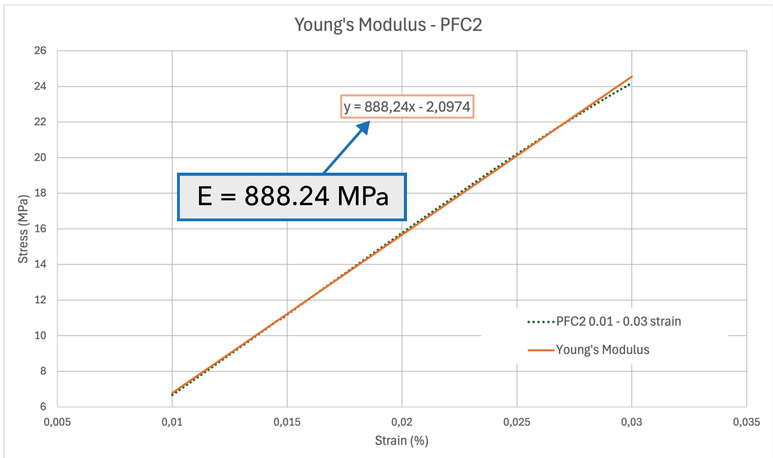


Figure 82: Stress-Strain curves of all cornstarch-containing hydraulic press samples

Figure 83 shows the Stress – Strain curve produced by compressive testing of sample PFC2, a sample containing fine sand and cornstarch. The highest Stress value of 29.79 MPa represents the Ultimate Compressive Strength of PFC2. The datapoints from 0.01 to 0.03 strain represent linear section of the graph. Plotting these datapoints gives Figure 83, with the slope of the datapoints describing a Young's Modulus of 888,24 MPa.

A line with slope a slope coefficient of 888,24 is plotted in the Stress – Strain curve of PFC2 and moved over the strain axis by 0.002 or 0.2% (Figure 83). The point where both lines intersect represents PFC2's Yield Strength of 27.21 MPa.





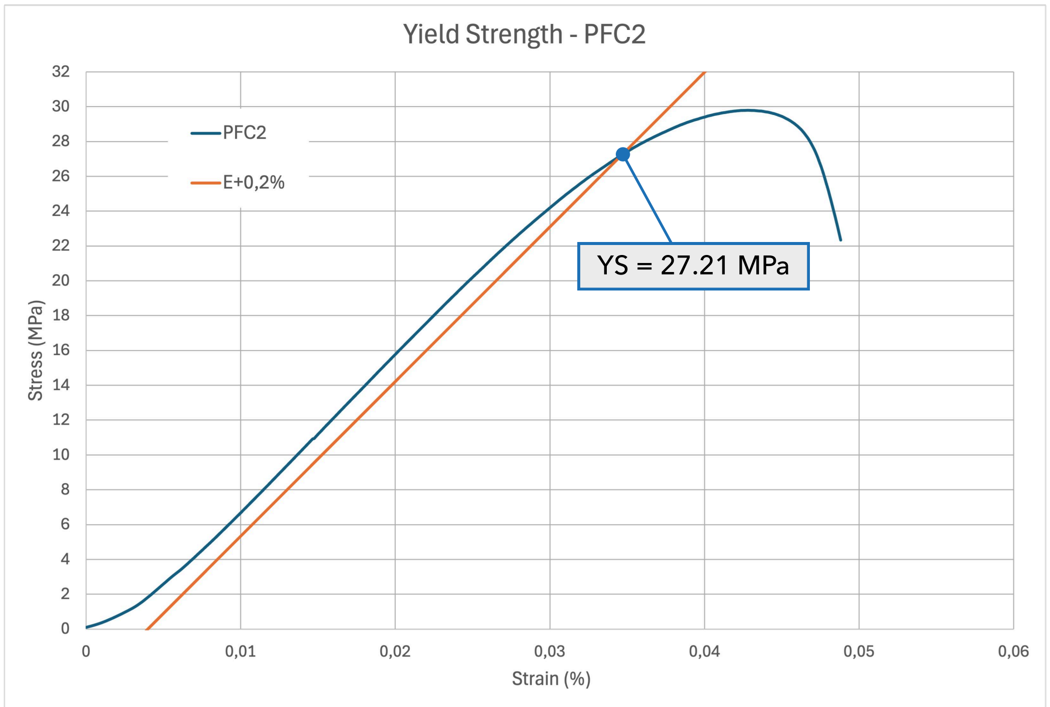


Figure 83: How the test results are analysed to find the Young's modulus, Yield Strength and Ultimate Compressive Strength.

Using this method, the mechanical properties of all CoRncrete samples can be found (Table 13). The average mechanical properties for each material composition are shown in Table 14. Samples containing potato starch have a higher SD for all mechanical properties compared to cornstarch-containing ones.

Sample	Young's Modulus (MPa)	Yield Strength (MPa)	Ultimate Compressive Strength (MPa)
PFP1	571.75	22.13	22.35
PFP2	514.79	24.63	24.96
PFP3	504.30	21.08	21.82
PFP4	239.12	7.36	11.84
PFP6	355.63	13.77	14.45
PMP2	801.58	29.72	31.35
PMP3	519.21	22.22	22.76
PMP4	319.80	9.77	9.97
PMP5	303.94	7.71	10.18
PMP6	332.39	7.89	12.37
PCP1	739.16	25.54	28.28
PCP2	489.84	20.77	23.20
PCP3	498.23	20.69	21.20
PCP5	397.44	10.94	11.78
PCP6	276.35	10.80	10.91
PFC1	657.76	27.39	27.43
PFC2	888.24	27.21	29.79
PFC3	745.39	29.71	30.98
PMC1	494.66	20.80	20.91
PMC2	593.55	19.56	20.66
PMC3	480.25	20.38	20.47
PCC3	356.06	14.06	15.25
PCC4	523.51	17.56	18.31
PCC5	517.98	17.45	18.30
OMC2	165.37	6.94	9.84
OMC3	106.98	5.56	7.80
OMC5	140.79	7.57	9.60

Table 13: Young's Modulus, Yield Strength and Ultimate Compressive Strength for each sample.

Material	Mean E (MPa)	SD	Mean YS (MPa)	SD	Mean UCS (MPa)	SD
PFP	437.12	136.49	17.79	7.10	19.08	5.63
PMP	455.38	212.35	15.46	9.98	17.33	9.43
PCP	480.20	170.21	17.75	6.58	19.07	7.52
PFC	763.80	116.34	28.10	1.39	29.40	1.81
PMC	522.82	61.68	20.25	0.63	20.68	0.22
PCC	465.85	95.12	16.36	1.99	17.29	1.76
OMC	137.71	29.32	6.69	1.03	9.08	1.11

Table 14: Young's Modulus, Yield Strength and Ultimate Compressive Strength for each sample.

7.3 Data Dispersion

Samples containing potato starch showed a minimum standard deviation of 6.58 and 5.63 for Yield Strength (YS) and Ultimate Compressive Strength (UCS), respectively. Alternatively, samples containing cornstarch had a maximum standard deviation of 1.99 and 1.81 for YS and UCS, respectively. This represents a 69.76% lower SD for YS and a 67.85% lower SD for UCS in cornstarch-containing samples. The high SD means the samples containing potato starch had a high degree of variance in the test data. Due to the difference in SD between potato starch and cornstarch-containing samples, further analysis is done to explain this difference. Visible cracks and curing time – the time between manufacturing and testing – are identified to potentially be of influence.

The impact of visible cracks and curing time on the UCS is analysed. The Ultimate Compressive Strength is chosen as the compared mechanical property as this value can be directly taken from the data, whereas the Yield Strength and Young's Modulus was read from the Stress-Strain curves. This makes the YS and E subject to human error margins, whereas inaccuracy of the UCS is minimized through the use of equipment.

7.3.1 Cracks

Table 15 shows the amount of cracks in sample compositions were cracks existed and the Ultimate Compressive Strength of each sample. To find a correlation between the Ultimate Compressive Strength and the number of cracks, both values were plotted against each other for each material composition (Figure 84). For each material composition, the sample with the lowest Ultimate Compressive Strength contained 0 cracks.

Sample	Ultimate Compressive Strength (MPa)	Cracks
PFP1	22.35	0
PFP2	24.96	1
PFP3	21.82	2
PFP4	11.84	0
PFP6	14.45	1
PMP2	31.35	0
PMP3	22.76	2
PMP4	9.97	0
PMP5	10.18	0
PMP6	12.37	0
PCP1	28.28	0
PCP2	23.20	1
PCP3	21.20	2
PCP5	11.78	0
PCP6	10.91	0

Table 15: Ultimate Compressive Strength and number of cracks of the samples containing cracks. Samples with cracks contain potato starch and fine sand (PFP), medium sand (PMP), and coarse sand (PCP).

Discussion

Difference in drying times within different layers of CoRncrete are likely the reason why visible cracks appear in CoRncrete samples. Manufacturing CoRncrete products of larger volumes might increase the risk of visible cracks. Cracks might have an adverse effect on waterproofing as water can collect in the cracks. Visible cracks might cause CoRncrete products to be perceived as low-quality. Additionally, mechanical properties such as fatigue might be affected through cracks. Figure 84 shows no correlation between the number of cracks and the Ultimate Compressive Strength. The PFP sample, containing fine sand and potato starch, with the highest UCS has one visible crack. Two cracks were observed in one sample for each material composition, but these samples did not have the lowest UCS for none of the compositions.

Varying drying times between layers of CoRncrete are likely responsible for the formation of visible cracks in the samples. Manufacturing larger CoRncrete products might further increase the risk of cracking. Cracks could negatively impact waterproofing, as water may collect within the cracks. Additionally, visible cracks might cause CoRncrete products to be perceived as lower quality. Mechanical properties such as fatigue resistance could also be affected by cracks. However, Figure 84 shows no correlation between the number of cracks and Ultimate Compressive Strength (UCS). For example, the PFP sample (fine sand and potato starch) had the highest UCS despite having one visible crack. Likewise, two cracks were observed in PFP3, PMP3 and PCP3, yet these samples did not exhibit the lowest UCS in compared to samples of their respective composition.

Conclusion

According to the data found in this study, visible cracks do not directly translate to a lower Ultimate Compressive Strength of CoRncrete structures. Cracks do not explain the data dispersion of mechanical properties observed in samples containing potato starch. However, cracks might negatively affect the perception, waterproofing and mechanical properties of CoRncrete products, making them undesirable.

Through implementation of manufacturing guidelines as described in section 5.4, formation of visible cracks can be minimised. Future research should identify potential detrimental effects of cracks and how to minimise cracks in manufacturing products of larger volumes.

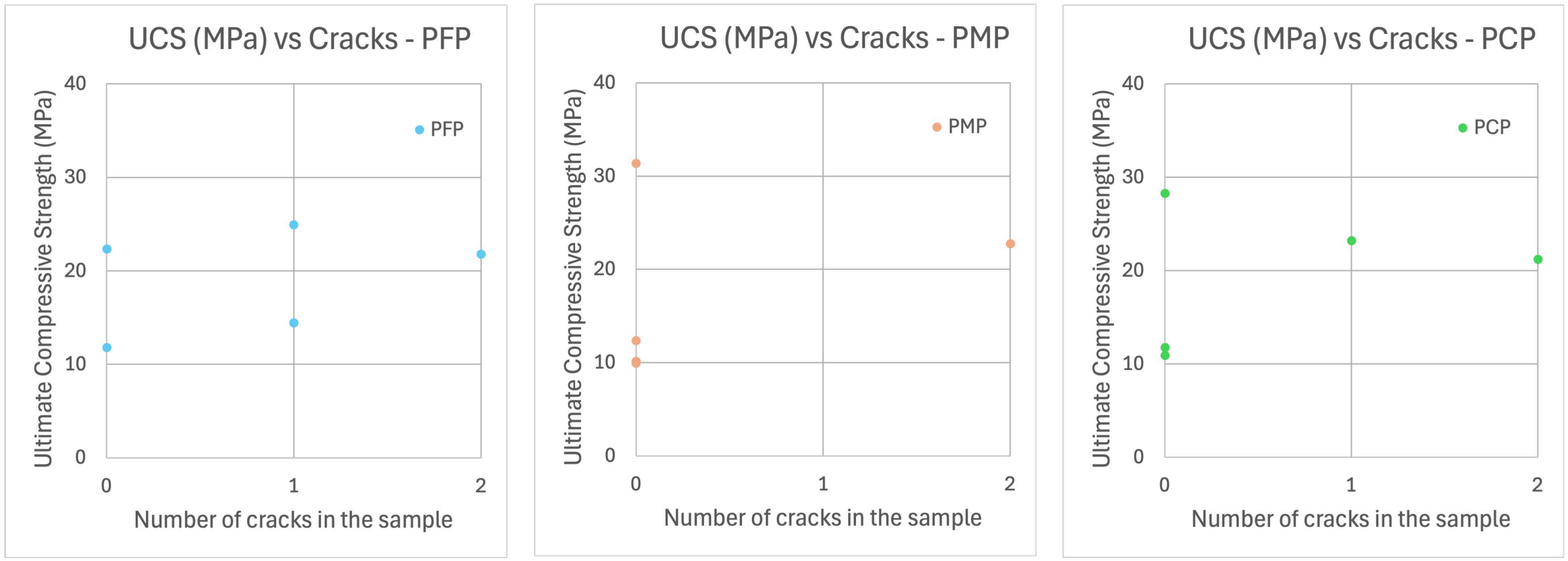


Figure 84: The number of cracks and Ultimate Compressive Strength plotted against each other for the samples containing fine sand and potato starch (a), medium sand and potato starch (b), and coarse sand and potato starch (c).

7.3.2 Curing time

Samples were manufactured on different dates but tested on the same. Due to time and machinery capacity required for manufacturing, samples were manufactured on different dates (Table 16). Increased amount of samples were manufactured per day due to the familiarisation of manufacturing (Table 16). Additionally, the manufacturing facility was not available during weekends, affecting manufacturing dates.

Figure 85 illustrates a strong correlation between Ultimate Compressive Strength and the curing time for potato starch-containing samples, while cornstarch-containing samples exhibited comparable Ultimate Compressive Strengths accompanied by comparable curing times (Figure 85).

Sample	UCS (MPa)	Manufacturing date	Test date	Curing time (days)
PFP1	22.35	06/01/2025	15/01/2025	9
PFP2	24.96	06/01/2025	15/01/2025	9
PFP3	21.82	06/01/2025	15/01/2025	9
PFP4	11.84	13/01/2025	15/01/2025	2
PFP6	14.45	13/01/2025	15/01/2025	2
PMP2	31.35	06/01/2025	15/01/2025	9
PMP3	22.76	06/01/2025	15/01/2025	9
PMP4	9.97	14/01/2025	15/01/2025	1
PMP5	10.18	14/01/2025	15/01/2025	1
PMP6	12.37	14/01/2025	15/01/2025	1
PCP1	28.28	06/01/2025	15/01/2025	9
PCP2	23.20	06/01/2025	15/01/2025	9
PCP3	21.20	06/01/2025	15/01/2025	9
PCP5	11.78	13/01/2025	15/01/2025	2
PCP6	10.91	13/01/2025	15/01/2025	2
PFC1	27.43	18/12/2024	15/01/2025	28
PFC2	29.79	18/12/2024	15/01/2025	28
PFC3	30.98	20/12/2024	15/01/2025	26
PMC1	20.91	20/12/2024	15/01/2025	26
PMC2	20.66	20/12/2024	15/01/2025	26
PMC3	20.47	20/12/2024	15/01/2025	26
PCC3	15.25	17/12/2024	15/01/2025	29
PCC4	18.31	17/12/2024	15/01/2025	29
PCC5	18.30	20/12/2024	15/01/2025	26

Table 16: All tested samples manufactured in the hydraulic press and their curing time

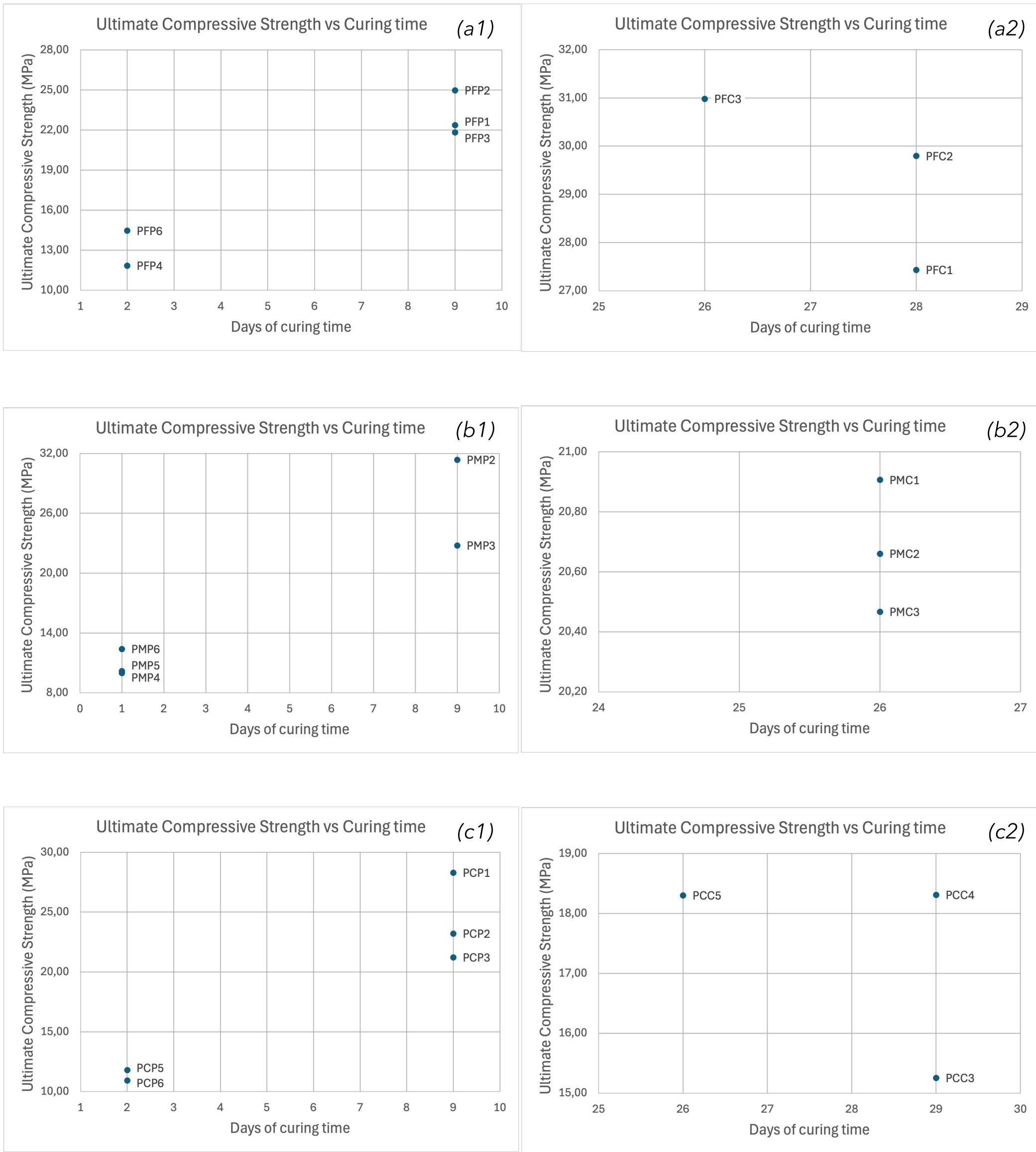


Figure 85: The Ultimate Compressive Strength and the days of curing time passed before testing. Samples containing potato starch and fine sand (a1), medium sand (b1), and coarse sand (c1). Samples containing cornstarch and fine sand (a2), medium sand (b2), and coarse sand (c2).

Discussion

A direct correlation is observed between the days of curing and the Ultimate Compressive Strength (UCS) of samples. PMP samples with a curing time of 1 days exhibited a mean UCS of 10.84 MPa, while increasing the curing time to 9 days resulted in a mean UCS of 27.05 MPa, representing a 59.63% increased UCS. Extending curing time from 2 to 9 days improved the UCS of PFP and PCP samples by 42.97% and 53.17%, respectively.

In previous research, Tulip et al. (2023) found that curing for 24 hours at 100 °C after gelatinisation in the oven was necessary to prevent mould. Besides mould prevention, they found this curing process increased the strength of CoRncrete. Tulip et al. (2023) attributed this characteristic to an accelerated recrystallisation process in gelatinised starch, called retrogradation, caused by the removal of moisture. Interestingly, Tulip et al. (2023) noted the importance of studying the effect of air-drying rather than oven drying. While air-drying included in the research through inexperience with material studies rather than as an interesting parameter, preliminary conclusions can be drawn.

Recalculating the mean mechanical properties of potato starch-containing samples after excluding those with a curing time of 2 days or less provides a more accurate analysis.

This comparison shows a reduction in data dispersion and improved Elastic Modulus (E), Yield Strength (YS), and Ultimate Compressive Strength (UCS), for all potato starch-containing samples.

Conclusion

According to the data found in this study, a shorter curing time directly affects the curing time. On average, increasing the curing time by 83.33% increases the UCS of potato starch-containing samples by 52.02%.

Disregarding samples with a curing time of 2 days or less reduced the data spread and increased the mean of the Elastic Modulus, Yield Strength and Ultimate Compressive Strength of potato starch-containing samples (Figure 86).

Manufacturing of CoRncrete should include a phase of air drying after shaping in the hydraulic press. The ideal circumstances and duration to achieve desired mechanical properties should be further researched.

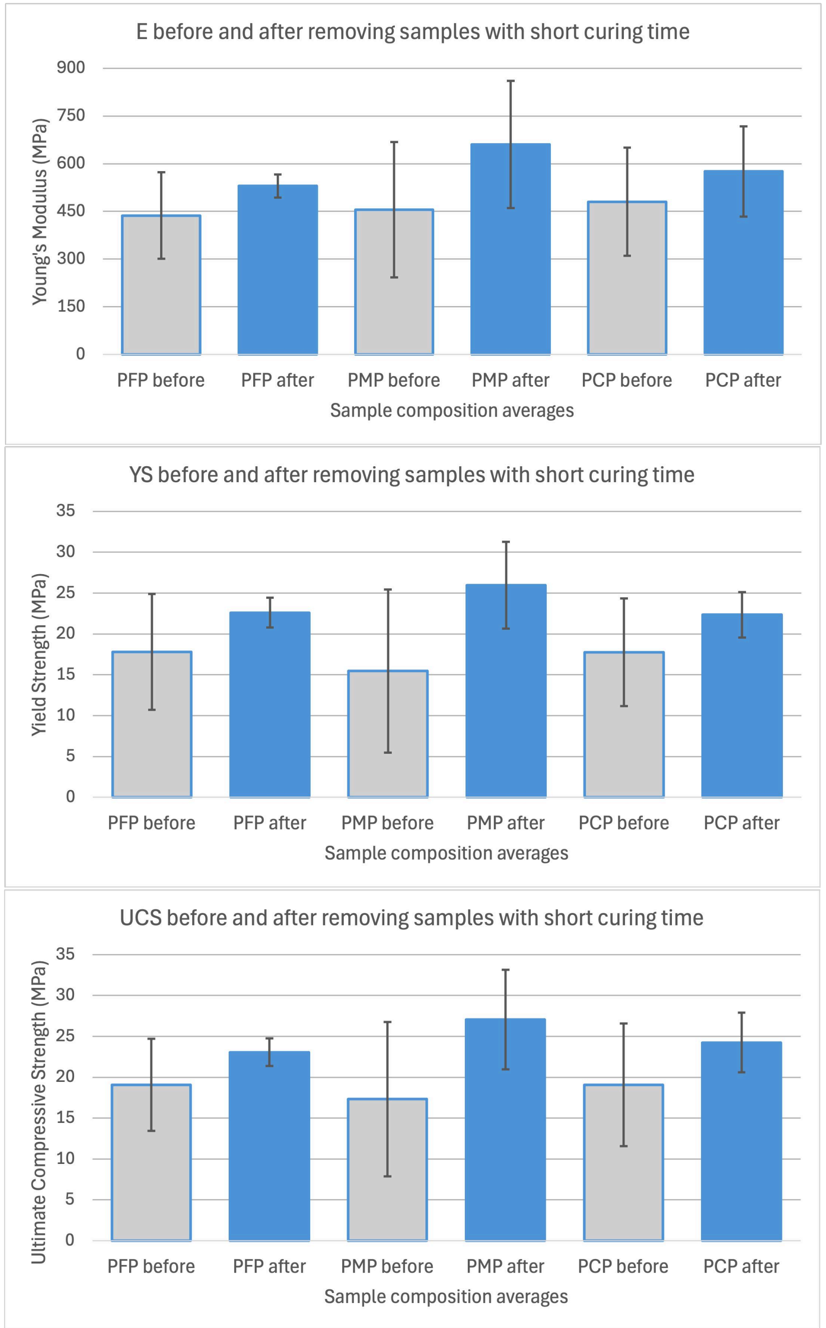


Figure 86: Mechanical properties before and after removing samples with short curing times

7.3.3 Conclusion - Data dispersion

The curing time after forming CoRncrete in the hydraulic press has a direct positive effect on the data spread, while cracks do not. Removing samples with a curing time of 2 days or less reduces the data spread while improving the mean mechanical properties of samples containing potato starch. On average, increasing the curing time by 83.33% increases the UCS of potato starch-containing samples by 52.02%. The Yield Strength and Young's modulus similarly improved. Manufacturing CoRncrete Grid Pavement should include a period of air drying after forming in the hydraulic press to improve the mechanical properties. Cracks should nevertheless be avoided as they might deter the perception, waterproofing and mechanical properties of CoRncrete at product scale.

To compare the mechanical properties of CoRncrete with different components, the samples with a curing time of 2 days or shorter are removed from the mean calculations. This results in the mean mechanical properties and standard deviation of Table 17.

Material	Mean E (MPa)	SD	Mean YS (MPa)	SD	Mean UCS (MPa)	SD
PFP	530.28	36.30	22.61	1.82	23.05	1.68
PMP	660.40	199.67	25.97	5.30	27.05	6.08
PCP	575.74	141.59	22.34	2.77	24.23	3.65
PFC	763.80	116.34	28.10	1.39	29.40	1.81
PMC	522.82	61.68	20.25	0.63	20.68	0.22
PCC	465.85	95.12	16.36	1.99	17.29	1.76

Table 17: Young's Modulus, Yield Strength and Ultimate Compressive Strength for hydraulic press samples, after removal of samples with a curing time of 2 days or less.

7.4 CoRncrete Composition

Table 18 shows the average mechanical properties of samples manufactured in the hydraulic press. To understand the effect of sand grains size and starch source on the mechanical properties of CoRncrete, the UCS is analysed. Additionally, the effect of material composition on the density is analysed to compare CoRncrete with other materials.

PFC and PMP have the highest E, YS and UCS compared to the other tested CoRncrete compositions (Table 18). Both sample are formed in the hydraulic press, but PFC uses finer sand (0.125–0.250 mm) and cornstarch, while PMP contains coarser sand (0.250–0.500 mm) and potato starch. To identify the CoRncrete composition most suitable for GP design, the mechanical properties of both compositions are further analysed.

Material	Mean E (MPa)	SD	Mean YS (MPa)	SD	Mean UCS (MPa)	SD
PFP	530.28	36.30	22.61	1.82	23.05	1.68
PMP	660.40	199.67	25.97	5.30	27.05	6.08
PCP	575.74	141.59	22.34	2.77	24.23	3.65
PFC	763.80	116.34	28.10	1.39	29.40	1.81
PMC	522.82	61.68	20.25	0.63	20.68	0.22
PCC	465.85	95.12	16.36	1.99	17.29	1.76

Table 18: Young's Modulus, Yield Strength and Ultimate Compressive Strength for hydraulic press samples, after removal of samples with a curing time of 2 days or less.

7.4.1 Sand grain size

Prior research highlights sand grain size as a critical factor in CoRncrete strength when manufactured in the oven (Kulshreshtha et al., 2017; Tulip et al., 2023). However, existing literature on CoRncrete formed in the hydraulic press utilizes Mars and Moon minerals (Roberts & Scrutton, 2023), leaving the effect of sand grain size unexplored. This study examines the impact of sand grain size on the UCS of cornstarch and potato starch-containing CoRncrete. The UCS is the most accurate mechanical property as it is directly represented by a data point.

Figure 87 illustrates the relation between average sand grain size and UCS of CoRncrete. The UCS of cornstarch-containing samples is negatively affected by an increased sand grain size (Figure 87), consistent with Kulshreshtha et al. (2017) who attributed this correlation to reduced starch-sand interaction surfaces per volume for increased sand grain sizes.

Potato starch-containing samples showed no clear correlation (Figure 87), rather, medium sand produces a 10.46% and 14.82% higher UCS than coarse and fine sand, respectively. Similarly, Tulip et al. (2023) concluded that 0.250-0.425 mm sand resulted in the highest

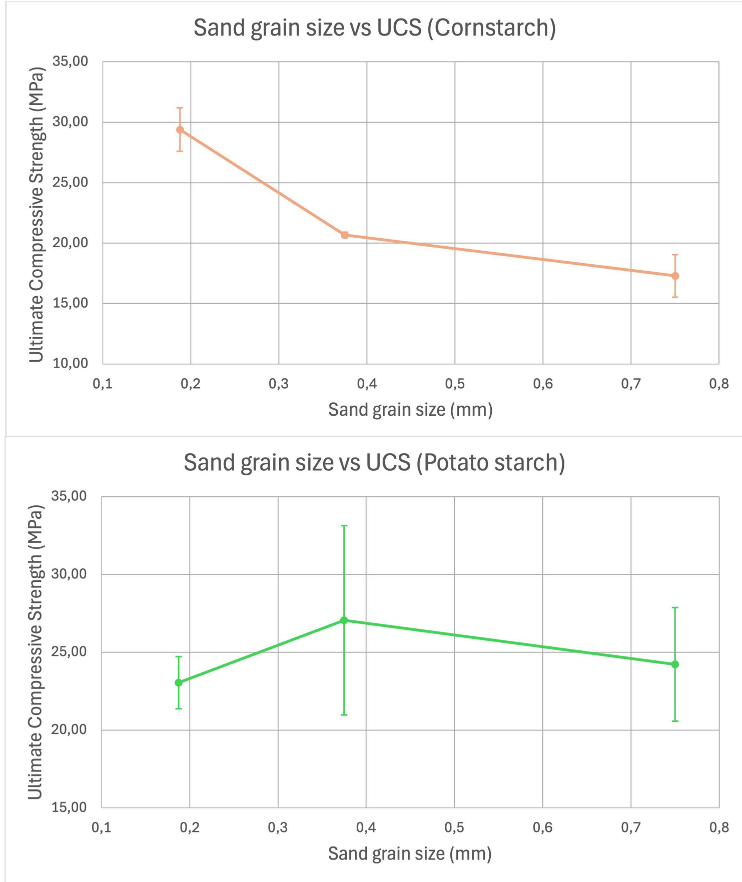


Figure 87: Sand grain size and corresponding UCS for cornstarch and potato starch

compressive strength, compared to 0.106-0.250 mm and 0.425-0.850 mm sand, likely due to the effect of slower curing in the oven compared to the microwave.

Both studies manufactured CoRncrete samples with cornstarch. The cornstarch-containing samples tested in this study follow the findings of Kulshreshtha et al. (2017), while potato starch-containing samples follow the trend of Tulip et al. (2023). The findings in this study exemplify the "complex multi-factor interactions" of starch gelatinisation (Roberts & Scrutton, 2023).

Additionally, tinkering and experiential characterisation found that 0.250 to 0.500 mm sand enhances the user experience of CoRncrete GP, while improving scalability and material quality, compared to other sand grain sizes.

7.4.2 Starch type

Due to the complexity of starch gelatinisation, Roberts & Scrutton researched the effect of different starch sources on the UCS of CoRncrete, finding potato starch to be the most optimal. The mean UCS of samples manufactured with cornstarch and potato starch, respectively are compared in Figure 88.

Similar to Roberts & Scrutton (2023) this study concludes that potato starch produces CoRncrete with a higher compressive strength than cornstarch. CoRncrete samples containing potato starch have a 8.32% higher mean UCS compared to samples containing cornstarch.

However, potato starch-containing samples cured for 9 days, while samples containing cornstarch cured for 26 to 29 days (Table 16). Increasing the curing time beyond 9 days for potato starch samples might enhance the mechanical properties, whereas further increasing the curing time is unlikely to significantly affect cornstarch-containing samples.

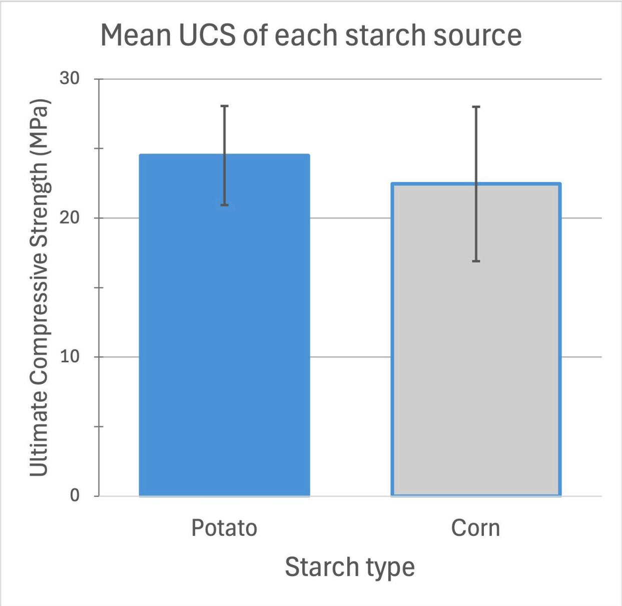


Figure 88: Mean Ultimate Compressive Strength of samples with Potato starch and Cornstarch

7.4.3 Density

Combining the density of CoRncrete with its mechanical properties allows for the identification of interesting potential applications in future research. The density of CoRncrete compositions was established through dividing the weight by the volume (Table 19).

An increased density correlates with an increased sand grain size for potato starch-containing CoRncrete (Figure 89). While samples containing cornstarch and 0.250 to 0.500 and 0.500 to 1.000 mm sand have comparable densities, PFC is more lightweight (Figure 89). 0.125 to 0.250 mm sand grains create the lightest CoRncrete regardless of the starch source.

CoRncrete composition	Density (kg/m³)
PFP	1659
PMP	1823
PCP	1876
PFC	1757
PMC	1872
PCC	1865

Table 19: The density of CoRncrete compositions

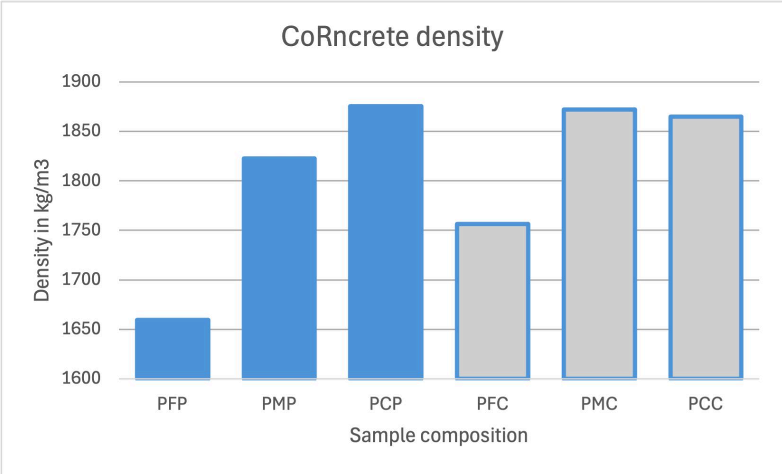


Figure 89: The density of different CoRncrete compositions

7.4.4 PFC vs PMP

Combining the Stress-strain curves of PFC1, PFC2 and PFC3 and PMP2 and PMP3, respectively, results in Figure 90. PFC has improved mean E, YS and UCS (Figure 90). Comparing the mean mechanical properties of PFC and PMP shows PFC has an approximately 16% higher mean E, 8% higher YS and 9% higher UCS (Table 20; Figure 90).

Analysing individual samples concludes that PMP2 has the highest recorded UCS of 31.35 MPa, followed by 30.98 MPa for PFC3, showing PMP containing samples have the potential to exhibit comparable mechanical properties to PFC-CoRncrete

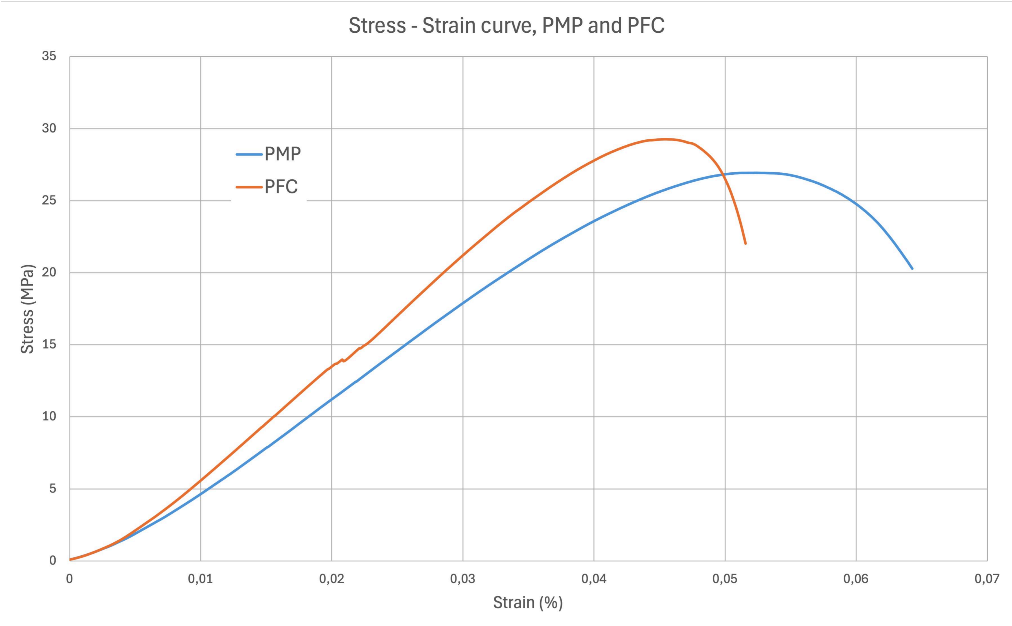


Figure 90: Average Stress-strain curves of PMP and PFC

Material	Mean E (MPa)	SD	Mean YS (MPa)	SD	Mean UCS (MPa)	SD
PFC	763.80	116.34	28.10	1.39	29.40	1.81
PMP	660.40	199.67	25.97	5.30	27.05	6.08

Table 20: Mechanical properties of PMC and OMC

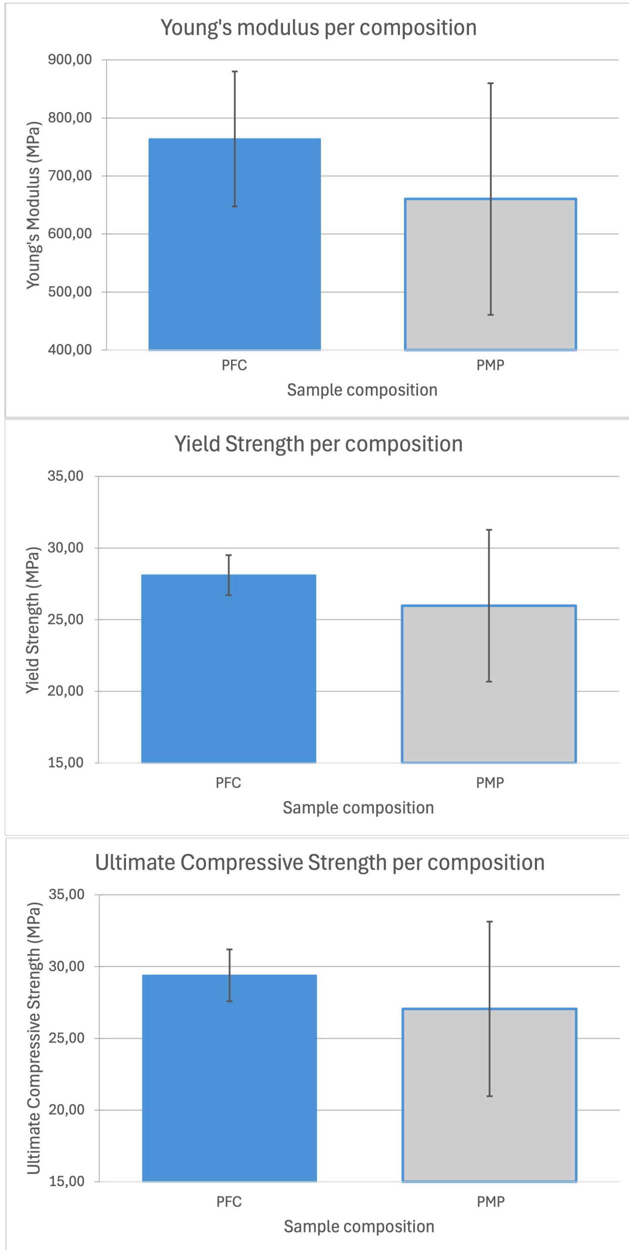


Figure 90: Average mean Young's Modulus, Yield Strength and Ultimate Compressive Strength of PMP and PFC

Discussion

Combining the density and the Young's Modulus of PFC and PMP, respectively, allows a comparison to existing materials in an Ashby chart (Figure 91). PFC and PMP are comparable to polymers. They are more dense and have a lower Young's Modulus than PE, the current material of TAWWA GreenGrids. PFC and PMP have a comparable density, but considerably lower Young's Modulus compared to concrete. The Ashby chart also shows how similar PFC and PMP are, putting the difference in mechanical properties into perspective.

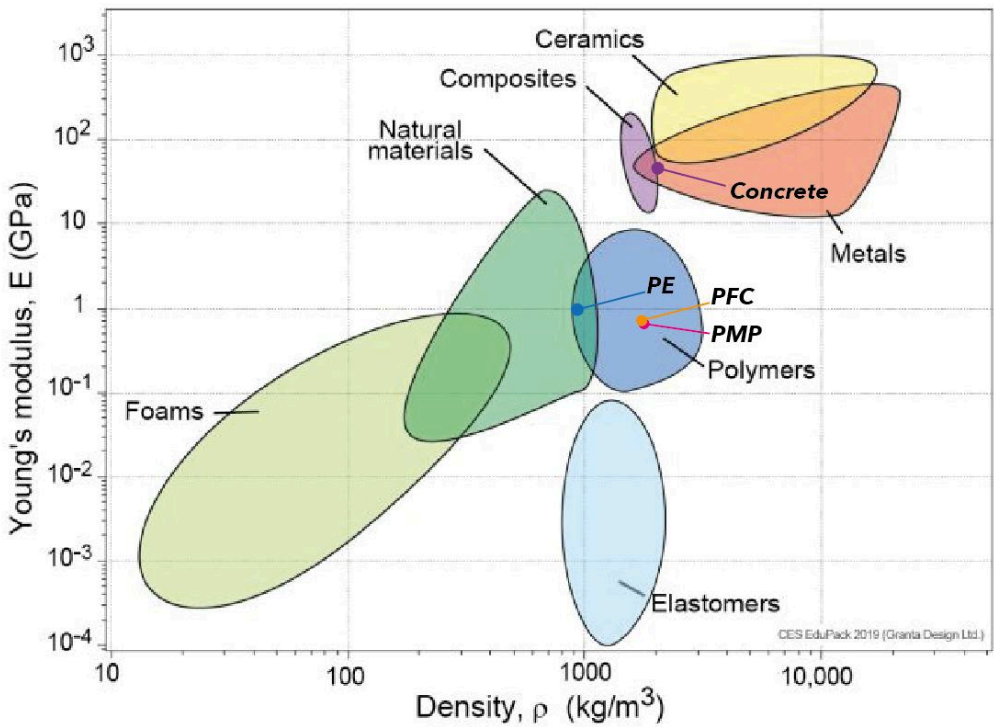


Figure 91: Ashby chart showing the relation between the Young's Modulus and density of materials, including PFC and PMP

7.4.5 Conclusion

CoRncrete containing cornstarch has a direct negative correlation with an increased sand grain size used in the material, while CoRncrete containing potato starch shows no correlation. CoRncrete containing potato starch has a 8.32% higher mean Ultimate Compressive Strength, showing both starch types are comparable.

CoRncrete formed in the hydraulic press containing 0.125 to 0.250 mm sand and cornstarch, called PFC-CoRncrete exhibits the highest mechanical properties. PMP-CoRncrete, containing potato starch and 0.250 to 0.500 mm sand, formed in the hydraulic press, exhibits the second best mechanical properties, while sample PMP2 exhibited the highest recorded UCS in this study (31.35 MPa). However, comparing the two CoRncrete compositions to other materials explains the insignificance of the difference between mechanical properties. While both materials are very similar, CoRncrete containing 0.250 to 0.500 mm sand and potato starch is likely more suitable for GP design due to improved scalability and end-product qualities. Additionally, PMP samples had a curing time of 9 days, compared to 26 to 29 days for PFC samples. Further increasing the curing time for PMP samples may improve the mechanical properties beyond PFC, while a strong increase of the mechanical properties of PFC caused by longer curing time is unexpected.

7.5 Oven

Similar to identifying the compressive behaviour of the samples manufactured in the hydraulic press, stress and strain is calculated from the data generated during testing and the measured initial diameter and height. Figure 92 shows the stress – strain curve for two sample compositions, PMC and OMC. Both samples contain medium sand and cornstarch, while PMC is formed in the hydraulic press and OMC is manufactured in the oven. Table 21 shows the mechanical properties for PMC and OMC. The UCS of both CoRncrete compositions is analysed in Figure 93.

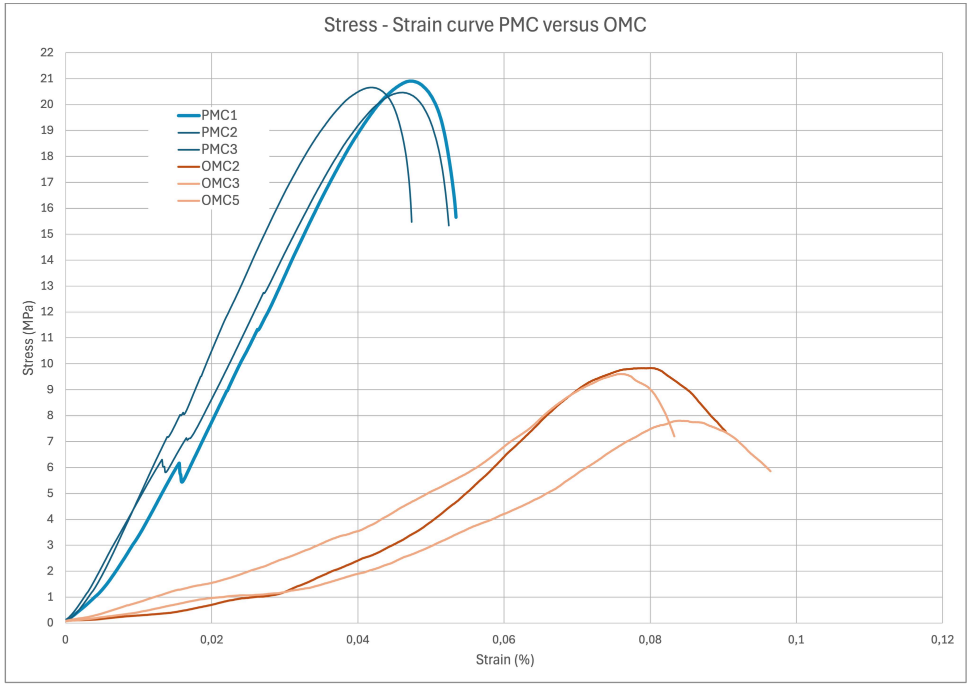


Figure 92: Stress-strain curves of PMC and OMC samples

Material	Mean E (MPa)	SD	Mean YS (MPa)	SD	Mean UCS (MPa)	SD
PMC	522.82	61.68	20.25	0.63	20.68	0.22
OMC	133.71	29.32	6.69	1.03	9.08	1.11

Table 21: Mechanical properties of PMC and OMC

7.5.1 Discussion

The mean Young's modulus (E), Yield Strength (YS), and Ultimate Compressive Strength (UCS) for PMC are close to four, three, and two times greater than those for OMC, respectively (Table 21; Figure 93).

The samples manufactured in the oven showed numerous small cracks (see section 5.4.1), suggesting unsupported cavities in the structure, likely resulting in lower mechanical properties compared to hydraulic press forming.

7.5.2 Conclusion

CoRncrete manufactured in the hydraulic press exhibits improved mechanical properties compared to CoRncrete manufactured in the oven, likely caused by the unsupported cavities in oven manufactured samples.

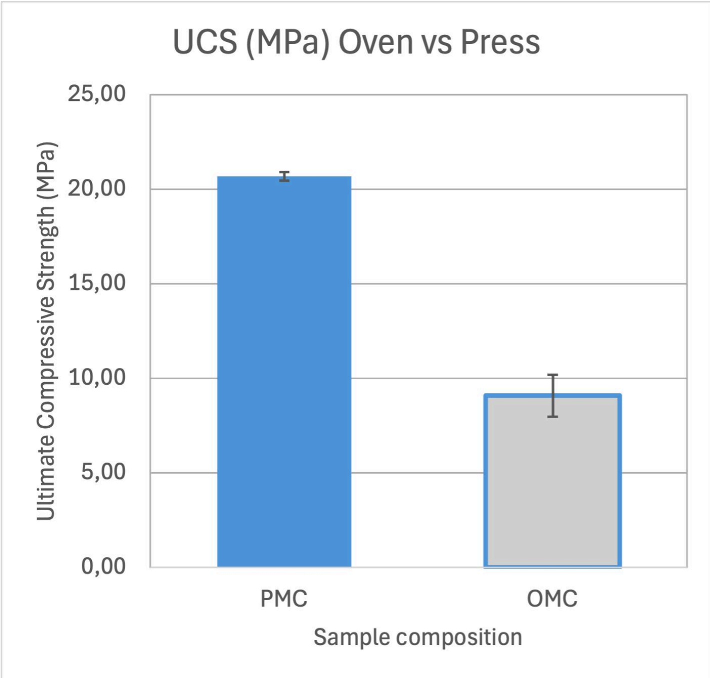


Figure 93: Comparing the UCS of PMC with OMC

7.6 Conclusion

An unconfined compressive test revealed technical aspects of CoRncrete and the effect of different components and manufacturing conditions. Initially, CoRncrete samples formed in the hydraulic press containing potato starch exhibited highly dispersed technical data compared to cornstarch-containing samples. Whereas cracks did not affect hydraulic press samples, a varying curing time was responsible for the high degree of data dispersion. An increased curing time positively affects the mechanical properties of CoRncrete manufactured in the hydraulic press, containing potato starch.

An increased sand grain size negatively effects the UCS of cornstarch-containing CoRncrete, similar to the results of Kulshreshtha et al. (2017), while the UCS of potato starch-containing samples does not correlate with the sand grain size. Rather, the medium sand size has a higher UCS compared to the finer and coarser sand grain size, aligning with the findings of Tulip et al. (2023). While prior research speculated the heating mechanism of the oven affects the starch-sand interaction differently from microwave heating (Tulip et al., 2023), this does not satisfy for this study as the difference is observed between starch sources.

On average, samples containing potato starch have a higher UCS compared to cornstarch-containing samples. This difference may further increase when increasing the curing time of potato starch-containing samples.

Increasing the sand grain size increases the density of potato starch-containing CoRncrete. While CoRncrete samples containing cornstarch and 0.250 to 0.500 mm and 0.500 to 1.000 mm sand have comparable densities, PFC is relatively lighter. CoRncrete with a 0.125 to 0.250 mm sand grain size results in the lowest density, regardless of starch source.

PFC-CoRncrete, made with 0.125 to 0.250 mm sand and cornstarch, exhibits the highest mechanical properties, while PMP-CoRncrete with potato starch and 0.250 to 0.500 mm sand ranks second, with PMP2 achieving the highest UCS in this study (31.35 MPa). Though PFC has higher mechanical properties, PMP-CoRncrete is likely better suited for GP design due to its scalability and product quality. Additionally, extending curing time beyond 9 days likely enhances the mechanical properties of PMP beyond PFC. The Stress-Strain curve and mechanical properties of PMP are shown in Figure 93 and Table 22, allowing for feasibility testing of the final concept.

Combining the density of PMP (Table 22) and the Young's Modulus puts CoRncrete in perspective to existing materials (Figure 94). PMP-CoRncrete is comparable to polymers but is denser and has a lower Young's Modulus than PE, the current material of TAWWA GreenGrids. PMP has a comparable density, but considerably lower Young's Modulus compared to concrete.

Lastly, this chapter aimed to identify the differnce between mechanical properties of CoRncrete oven manufactured and hydraulic press formed CoRncrete. Hydraulic press forming at least doubles the mechanical properties of CoRncrete compared to oven manufacturing.

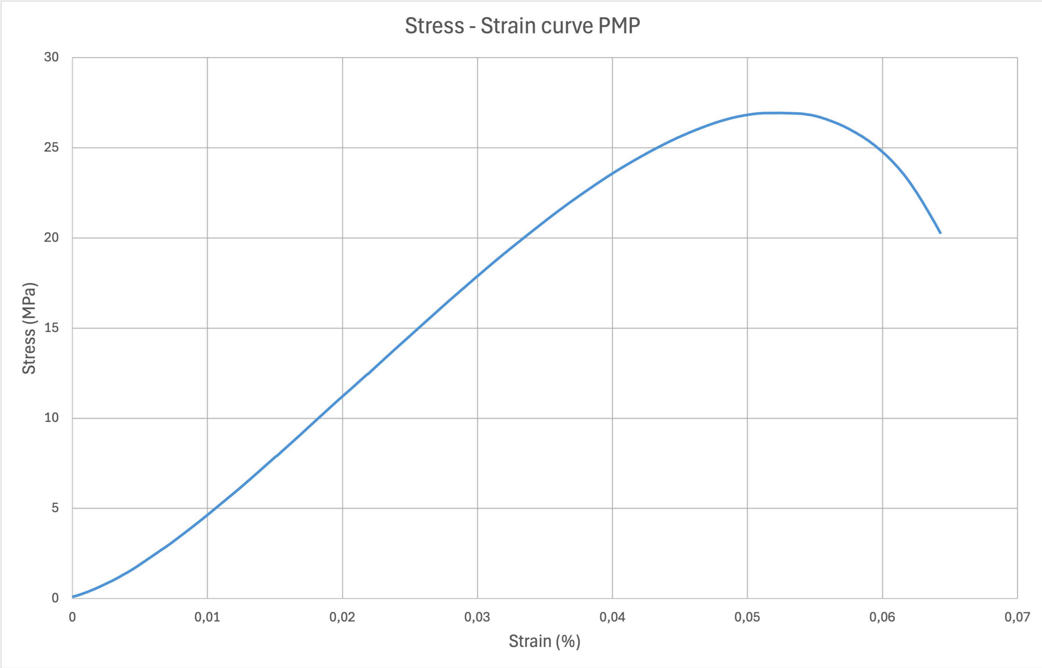


Figure 93: Stress-strain curves of PMC and OMC samples

Density (kg/m³)	Young's Modulus (MPa)	Yield Strength (MPa)	Ultimate Compressive Strength (MPa)
1823	660.40	25.97	27.05

Table 22: Mechanical properties and density of PMP

Limitations

The drying time for cornstarch and potato starch-containing samples varied, resulting in results that were difficult to compare. Additionally, a samples size of three per composition was already the minimum and removing the samples with a curing time of 2 days or less even resulted in a sample size of 2 for PMP.

Future Studies

Future studies should research the mechanical properties of CoRncrete manufactured in the hydraulic press with a larger sample size, while trying to improve the mechanical properties with sustainable additives.

Additionally, the mechanical properties for samples containing cornstarch and potato starch with an equal curing time should be studied. Identifying the ideal curing conditions can further optimise the production of high-strength CoRncrete.

Reflection

Performing mechanical testing and analyses was a first time for me. This created a multitude of uncertainties and likely resulted in mistakes. The difference in curing time could have been prevented by storing the samples in air-tight bags. Analysing the mechanical properties in Excel was tedious and required multiple iterations due to inexperience. As each sample produced a different amount of datapoints, manual aligning of the datapoints was required to create average Stress-Strain curves.

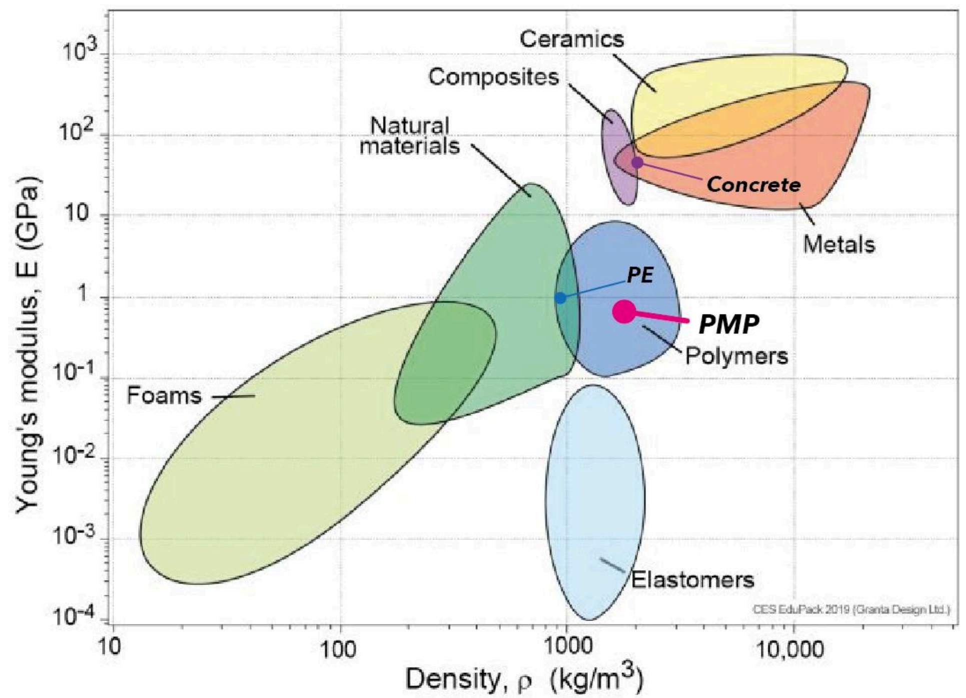


Figure 94: Ashby Chart with PMP-CoRncrete

8 final concept

How can the research be concluded into a concept design?
How does the concept compare to the current market?

CoRnGrid

Your sustainable solution to a climate adaptive city

8.1 Experience Vision

To "recognise a visionary path through the unknown, towards a future application", Karana et al. (2015) suggests articulating a Materials Experience Vision. Since the application in this study has been determined as Grid Pavement, the Materials Experience Vision helps to design GP that enhances the user experience of CoRncrete.

From the experiential characterisation (Chapter 6), the relation between the different levels of user experience of CoRncrete containing 0.250 to 0.500 mm or Medium sand were identified. Three findings could be concluded:

1. Users were comforTable with holding Medium because it looks ordinary and warm.
2. Users recognised the sand grains, expected the material to be weak and soft, but due to manufacturing it felt surprisingly strong
3. Users were attracted to the ordinarity and naturality, while caressing the texture and testing the toughness/softness surprised users.

As a result of these characteristics, it is envisioned that:

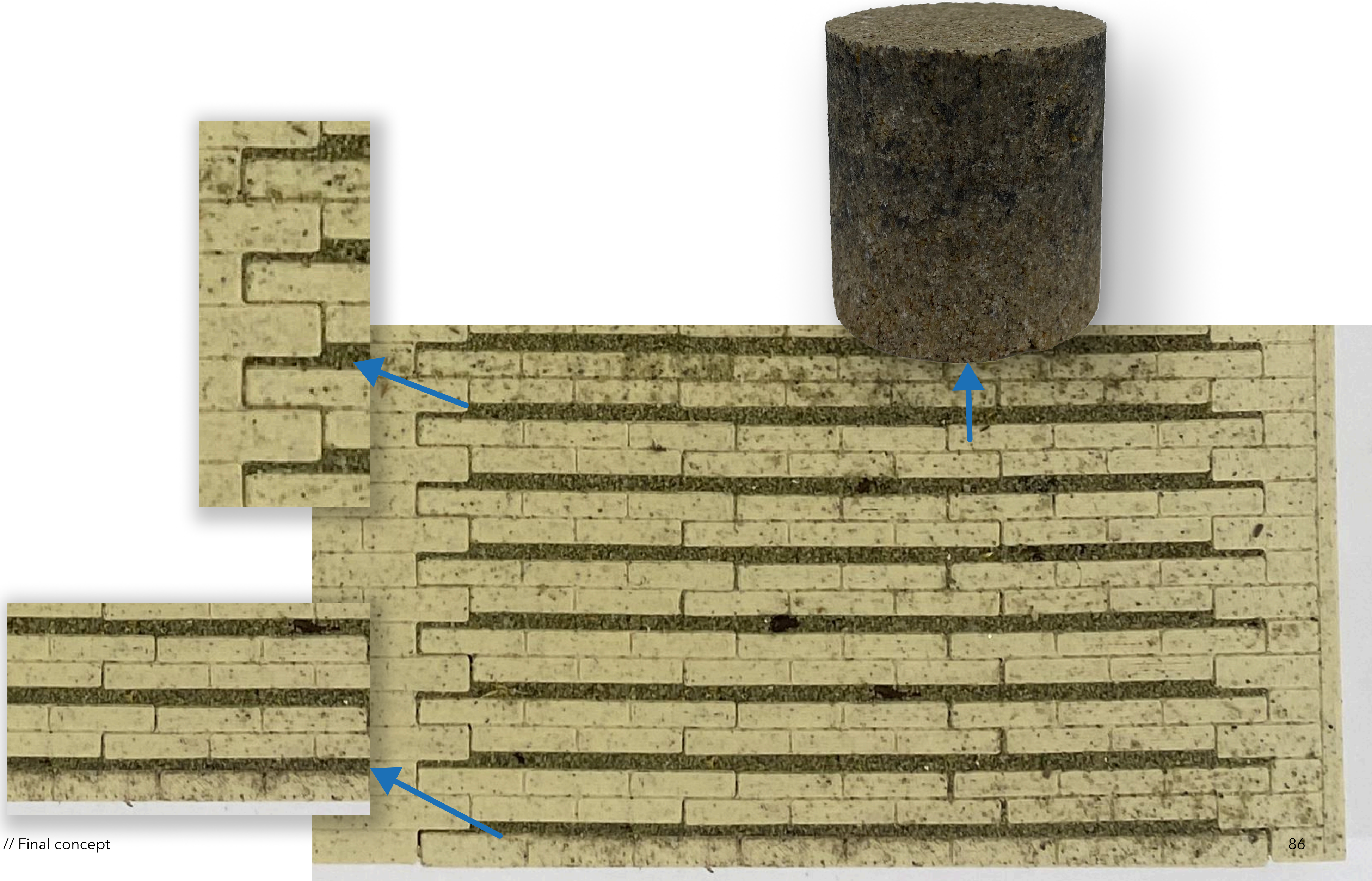
"CoRncrete Grid Pavement transforms the public space, **seamlessly integrating vegetation** into **infrastructure**, creating **harmonious** urban areas. CoRncrete's **familiar** appearance creates **acceptance** of a **novel material**, while its **unique texture** sparks **curiosity** and **excitement**."

This vision aims to improve the desirability of Grid Pavement design as it fits the needs of Municipalities and (Landscape) Architects. Municipalities and (Landscape) Architects want GP to tackle climate related issues, made from a sustainable material to reduce the environmental impact, while making the public space attractive, reliable and manageable.

CoRncrete GP could bridge the gap between vegetation and infrastructure that is caused by urbanisation. Concrete or plastic GP creates a hard divide between man-made, inorganic materials and nature, while CoRncrete's natural appearance allows for a seamless integration of vegetation and infrastructure. This allows CoRncrete GP to contribute to harmonious, climate adaptive urban areas. The visual sand grains in CoRncrete create a familiar appearance and a unique texture that introduces curiosity and excitement through a tactile experience. Through its familiar appearance CoRncrete aims to overcome perceived uncertainty caused by the material's novelty, likely accelerating adoption. CoRncrete's unique texture adds a dimension of curiosity and excitement that promotes and inspires use of the material.

8.1.1 Seamless integration of vegetation into infrastructure

The differently sized spacers create a ‘fading’ effect, where Grid Pavement transitions into impervious pavement through smaller strokes of vegetation towards the edges. This allows for a seamless integration of vegetation rather than hard divisions between vegetation and impervious surfaces. Additionally, CoRncrete’s natural character integrates the vegetation into robust infrastructure.



8.1.2 Shape & dimensions

In the Netherlands bricks are often used for housing and roads in residential areas (Totaaltegel, n.d.). The aesthetic of bricks is perceived as classical yet timeless while providing a hand-crafted appearance (Totaaltegel, n.d.). The shape CoRnGrid GP follows that of pavement bricks and commonly used patternscomplimenting the ordinary and recognisable user experience of CoRncrete.

The Netherlands construct roads in residential areas with maximum speeds up to 50 km/h mainly from pavement bricks. Taking bricks out allows for maintenance to underground pipes and cables, while the bricks can be reinstalled after. Individual bricks can be replaced with new ones to provide maintenance to the roads itself. Additionally, the texture of brick roads produces sound when driven on too fast, increasing the safety of residential areas paved with bricks.

In the Netherlands, three shapes are most commonly used for brick pavement: the 'Waalformaat', measuring 200 by 50 mm, 'Dikformaat', measuring 210 by 70 or 200 by 65 mm or 'Keiformaat' measuring 210 by 100 mm (L x W) (Figure 95). Dikformaat and Keiformaat bricks are typically used for roads and parking lots, whereas the Waalformaat is mainly used for pedestrian traffic. Dikformaat bricks give a traditional top surface, making them the most suitable for CoRncrete GP. Dikformaat bricks are generally between 60 and 80 mm high (Bestratingsweb.nl, n.d.-a), where a minimal thickness of 60 mm is recommended for driveways (MBI De Steenmeesters, n.d.). Additionally, as initially recommended by participant 4 of the experiential interviews, bricks used for driveways should have a chamfered edge.
The shape of the redesign is based on 200 by 65 by 80 mm 'Dikformaat' bricks to provide a common, traditional appearance for heavy traffic infrastructure.

Figure 95: Standard sizes of brick pavers. Waalformaat measuring 200 by 50 by 60 mm (left) (Klinkervisie B.V., n.d.), Dikformaat measuring 200 by 65 by 60 mm (middle) (Jonk Sierbestrating, n.d.), Keiformaat measuring 200 by 100 by 70 mm (right) (Bricks and Stones, 2025).

In order to prevent bricks from moving and to systematically pave surfaces, patterns are used in brick paving (Figure 96). Integrating a traditional brick pattern in the GP module design allows for recognisability and integration into brick paved infrastructure.

Common patterns in Dutch streets are the 'Halfsteenverband', 'Elleboogverband' and 'Visgraatverband' (Figure 96; Bestratingsweb.nl, n.d.-b). Alternating patterns often indicates different traffic zones. The 'Visgraat' or 'Elleboogverband' are often used in roads due to the strength of the pattern (Bestratingsweb.nl, n.d.-b), while the 'Halfsteenverband' is often used for parking and pedestrian areas. The CoRnGrid follows the 'Halfsteenverband' as the pattern creates a distinction between brick roads and parking. Additionally, the straight angles and linear pattern of the 'Halfsteenverband' allow for systematic integration of vegetation while simplifying compatibility with bricks.
Additionally, the 'Visgraatverband' and 'Halfsteenverband' create a more complex and modern pattern, while the 'Halfsteenverband' creates a continuous, linear pattern, enhancing the ordinary and recognisable appearnce of CoRncrete. The 'Wildverband' was also considered to add organic irregularities to the pattern, enhancing CoRncrete's natural appearance.

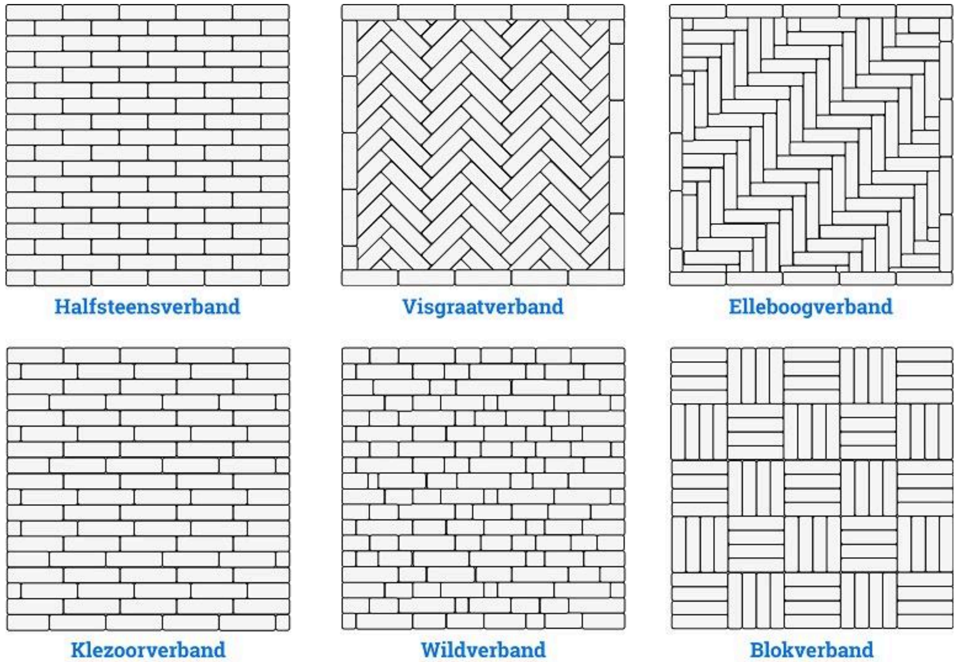
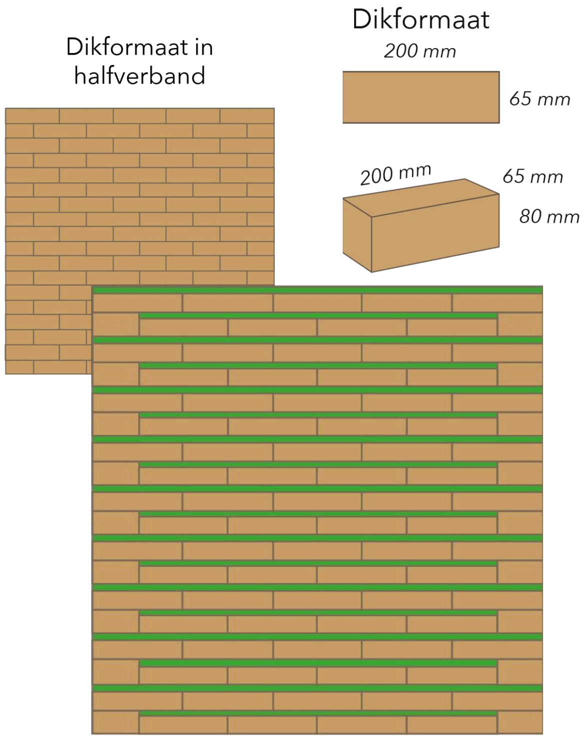
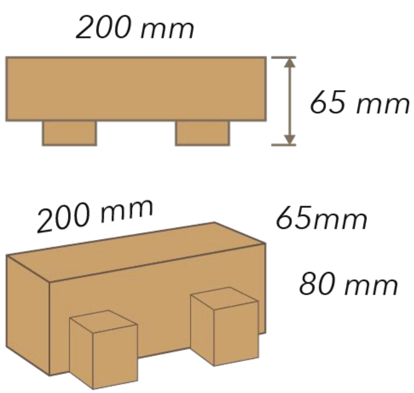


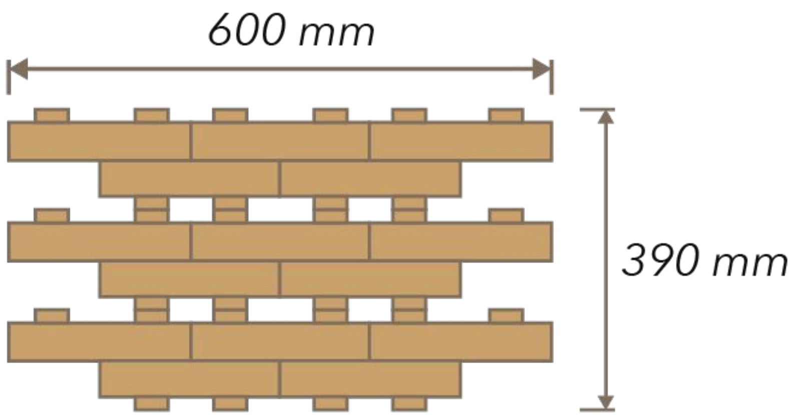
Figure 96: Standard brick pavement patterns (Bestratingsweb.nl, n.d.-b)

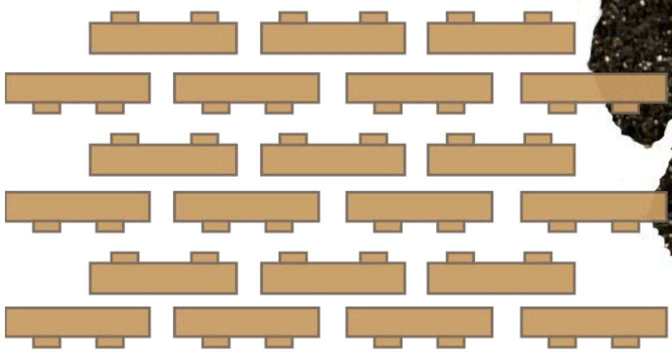
8.1.3 Product evolution

CoRnGrid is designed with 'Dikformaat' bricks in a 'Halfverband' as inspiration. Cropping the bricks allows for a continuous line of vegetation. Spacers below the height of the brick ensure structural strength while leaving the visible line of vegetation uninterrupted. Combining these cropped bricks with invisible spacers into a Halfverband, spacers oriented towards each other, creates open cells of 30 mm wide. Combining these separate bricks into one module results in CoRnGrid.







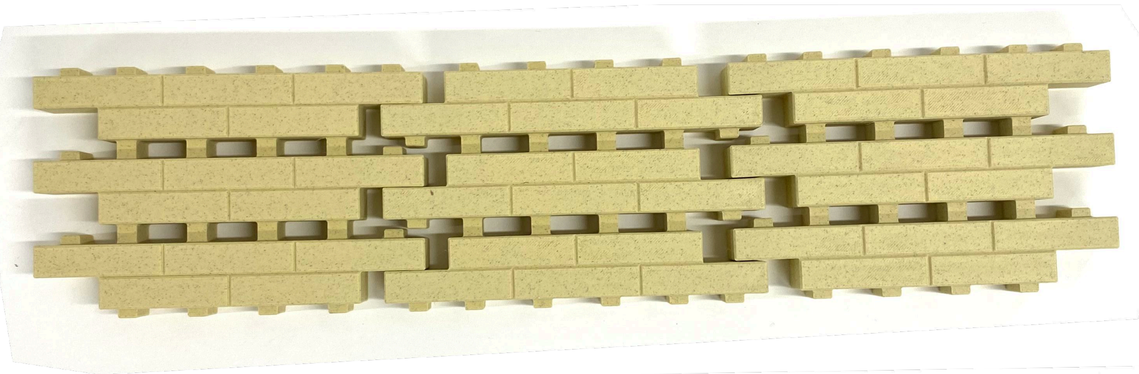


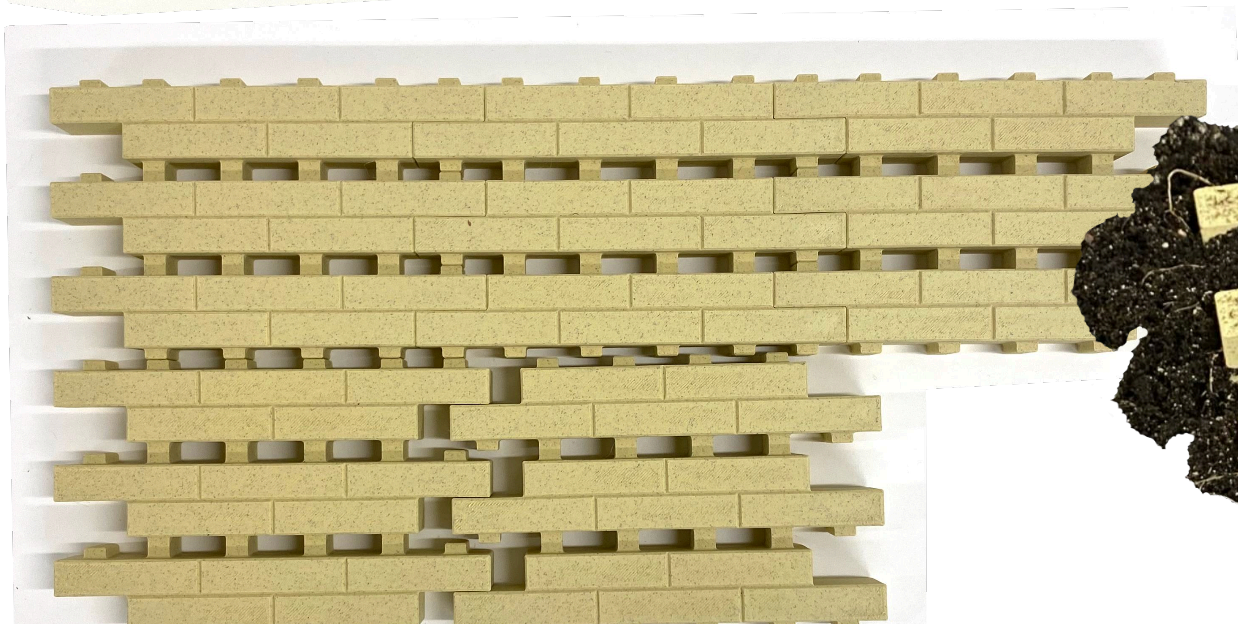
8.1.4 Installation

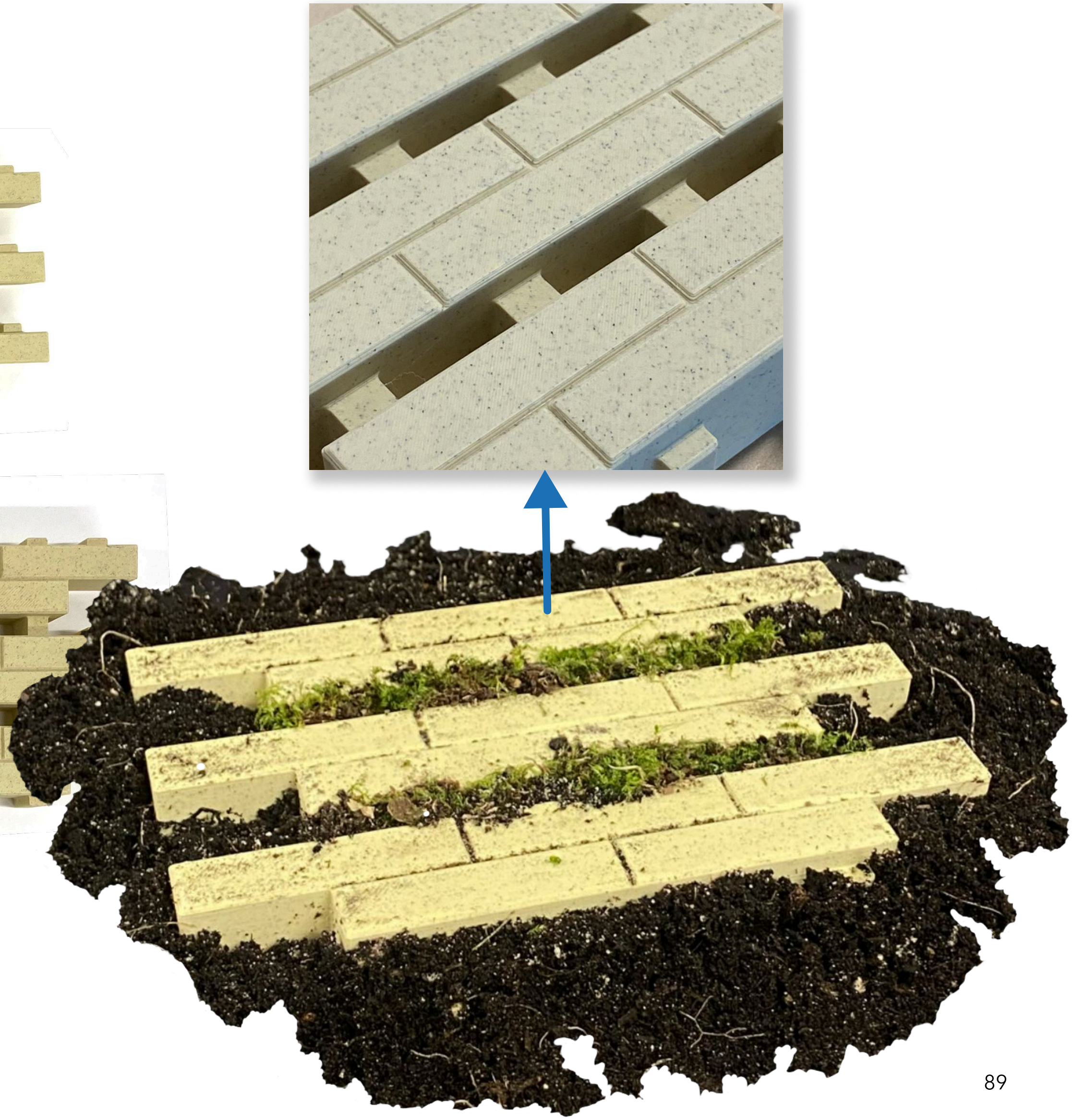
To form larger surfaces, multiple modules can be connected. By turning one module 180°, two modules can interlock to create a pattern. Connecting three modules in the width of a parking space provides a vegetated area with a width of 1600 mm, likely improving accessibility. Users would walk on fully paved sections between the vegetated areas rather than over the Grid Pavement. This prevents users with walking aids or high heels from getting stuck in the open cells.

8.1.5 Grooves

Grooves in the top surface of CoRnGrid modules create the illusion that the surface is made up of multiple bricks. Additionally, this might improve the skid-resistance of CoRnGrid pavement, an important requirement for pavement.







8.1.6 Transportation

Each Grid Pavement module measures 600 by 390 by 80 mm. This allows for efficient transportation on 800 by 1200 mm Euro palettes (Figure 97) and 800 by 600 mm Display palettes (J. Heebink Transport, 2022).

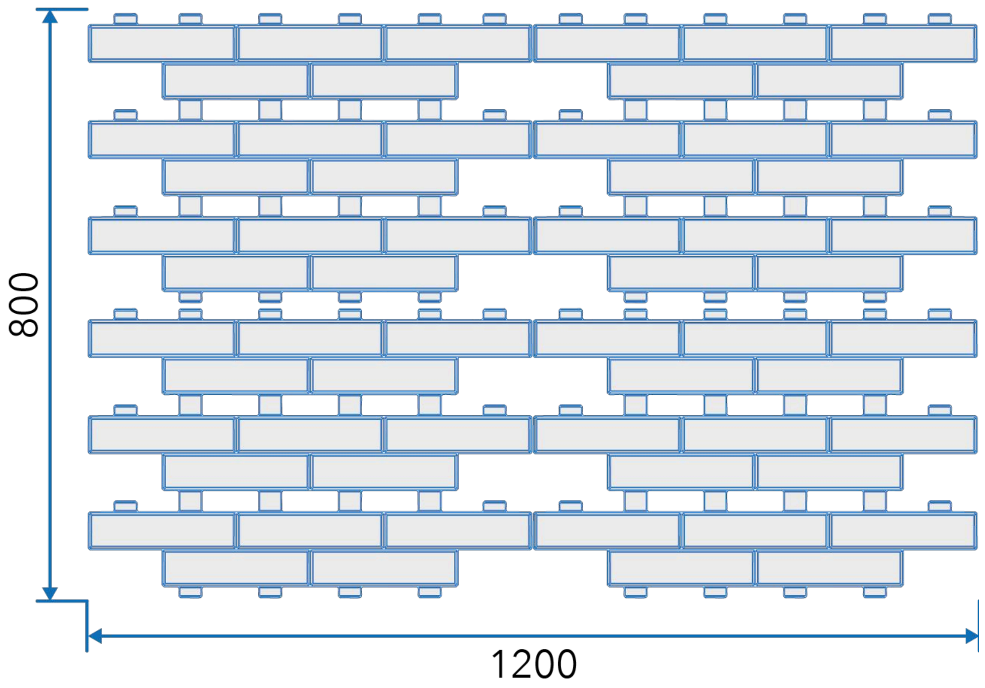


Figure 97: CoRnGrid efficiently placed on palettes

8.1.7 Weight

PMP-CoRncrete has a density of 1823 kg/m³, making one CoRnGrid element weigh 23.26 kilograms. Current TAWWA GreenGrids weigh 13 kg per square meter whereas CoRnGrid weighs approximately 99 kg/m², resulting in an increased weight of about 87%. However, since installation can be done mainly with machinery, this does not pose a direct threat to workplace safety. Future research should conclude the optimal installation of CoRnGrid.

8.1.8 Costs

A rough estimate shows CoRncrete costs €0.4592 per kg. This results in a cost of €10.68 per module. Energy and potato starch costs are the highest contributors. Considering insecurities, a price range of €12 to €15 is assumed.

8.2 Technical feasibility

Michelin, a well-known tire manufacturer sells the X® MULTI™ F / D / T / Z (22.5). This tire is used for heavy trucks with load index 160, being able to withstand 9000 kg per axis. Each tire is 385 mm wide, 65 mm high and fits 22.5-inch rims. Each tire should be pressurised to 9 bar or 0.9 MPa. The technical feasibility of CoRngrid was tested through a Finite Element Analysis (FEA) of the 3D model, assuming a truck using Michelin X® MULTI™ F / D / T / Z (22.5) parks on top, loaded to the maximum capacity of the tires. A safety factor of 2.5 was used to minimise the effects of uncertainties connected with material innovation.

A approximation of pavement-tire contact surface is calculated through A = F/P, where A is the contact area, F is the force, and P is the pressure in the tire. The load can be calculated through F=m*g, where F is the force, m is the mass of 4500 kg per tire and g is the gravitational constant of 9.81 mm/s². Each tire is loaded with a force of 44145 Newton. The pressure in the tire is 0.9 MPa, leading to a surface area of: A = 44145/0.9 = 49050 mm². The width of the tire in contact with the surface is assumed to be 300 mm, leading to a contact area length of 163.5 mm. Including the safety factor, each tire is loaded with 110362.5 Newton. An area of 300 by 163,5 mm is loaded with 110362.5 Newton using FEA. As shown in Figure 98, the area of the CoRnGrid that resists the load is actually less than the tire surface: 24846.69 mm².

As material input, the mechanical properties of PMP-CoRncrete were used (Table 23).

Young's Modulus (MPa)	Yield Strength (MPa)	Ultimate Compressive Strength (MPa)
660.40	25.97	27.05

Table 23: The mechanical properties of PMP - CoRncrete

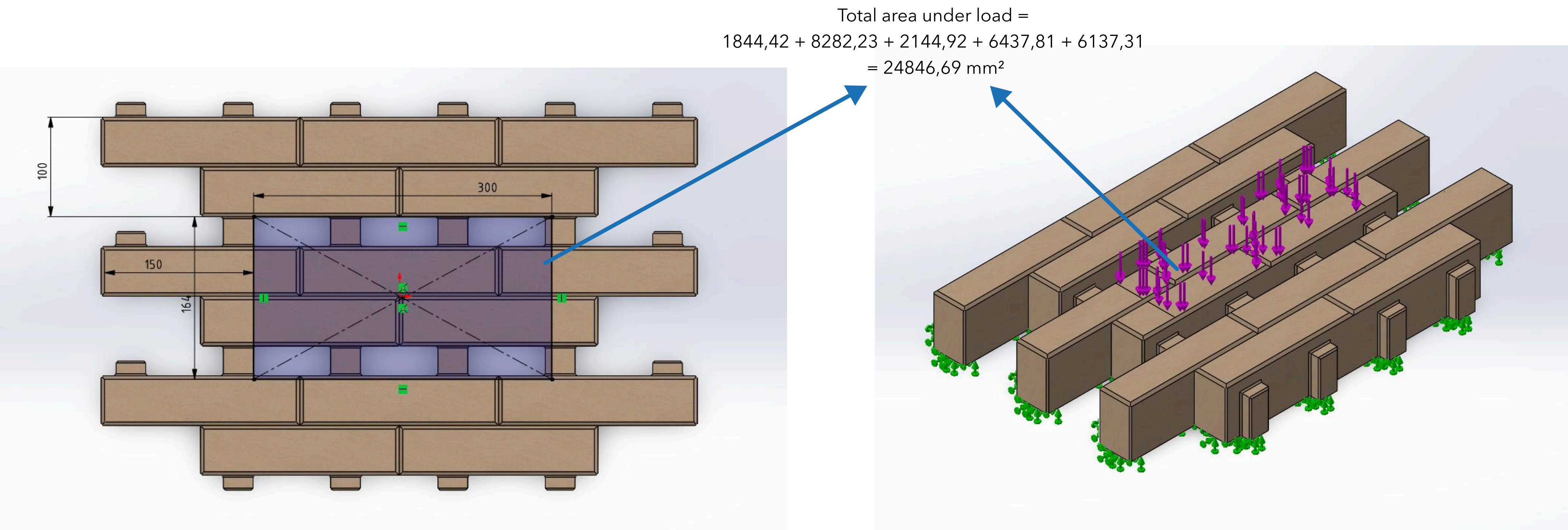


Figure 98: Restraints and loads of FEA

8.2.1 Stress

The maximum stress measured in CoRnGrid under a load of 110362.5 Newton is 8.73 MPa, a stress value approximately thrice lower than the Yield Strength of PMP-CoRncrete (25.97 MPa) (Figure 99). The highest stress values were observed in the transition from brick to spacer. These areas should be the focus of redesign. However, since the magnitude of the maximum stress with a safety factor of 2.5 included, is thrice lower than the Yield Strength, failure is unexpected. Testing CoRnGrid on repetitive loading could result in failure in these areas, but is not performed in this study.

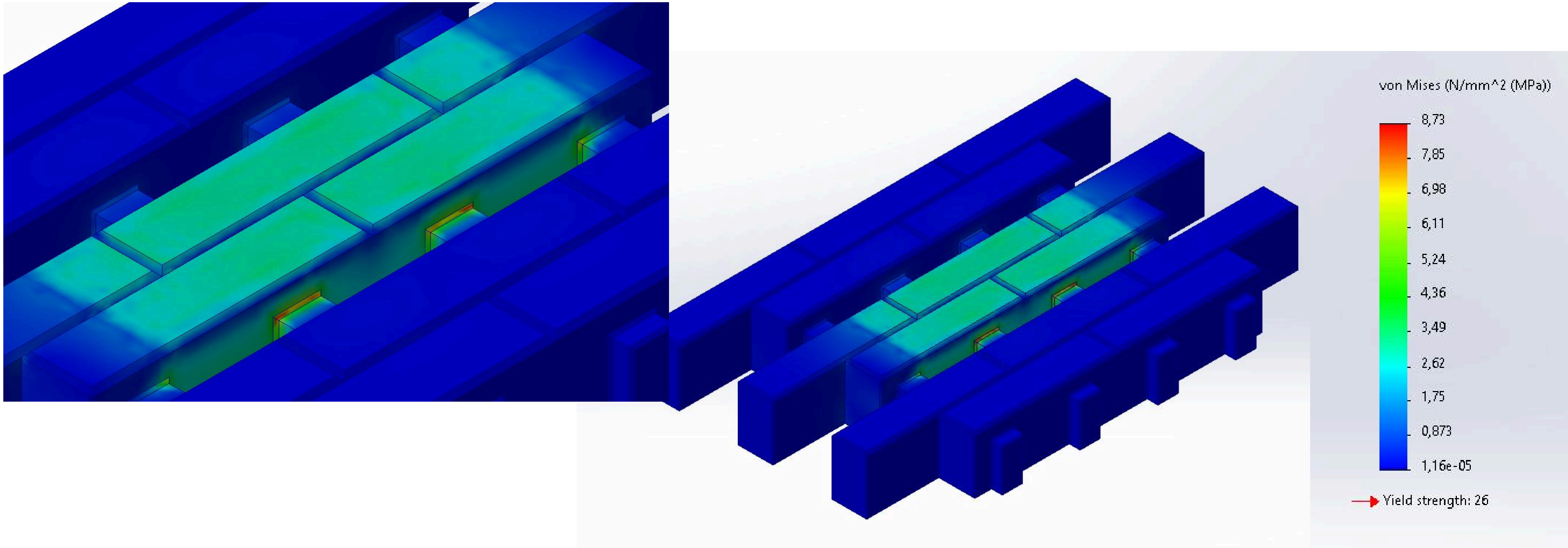


Figure 99: Stress analysis from FEA

8.2.2 Deformation

A maximum deformation of 0.438 mm was observed in the FEA (Figure 100). The highest deformation was situated on the top surface of the CoRnGrid module. Additional analysis of the strain shows a maximum strain of 0.0079, well in the elastic region of PMP-CoRncrete.

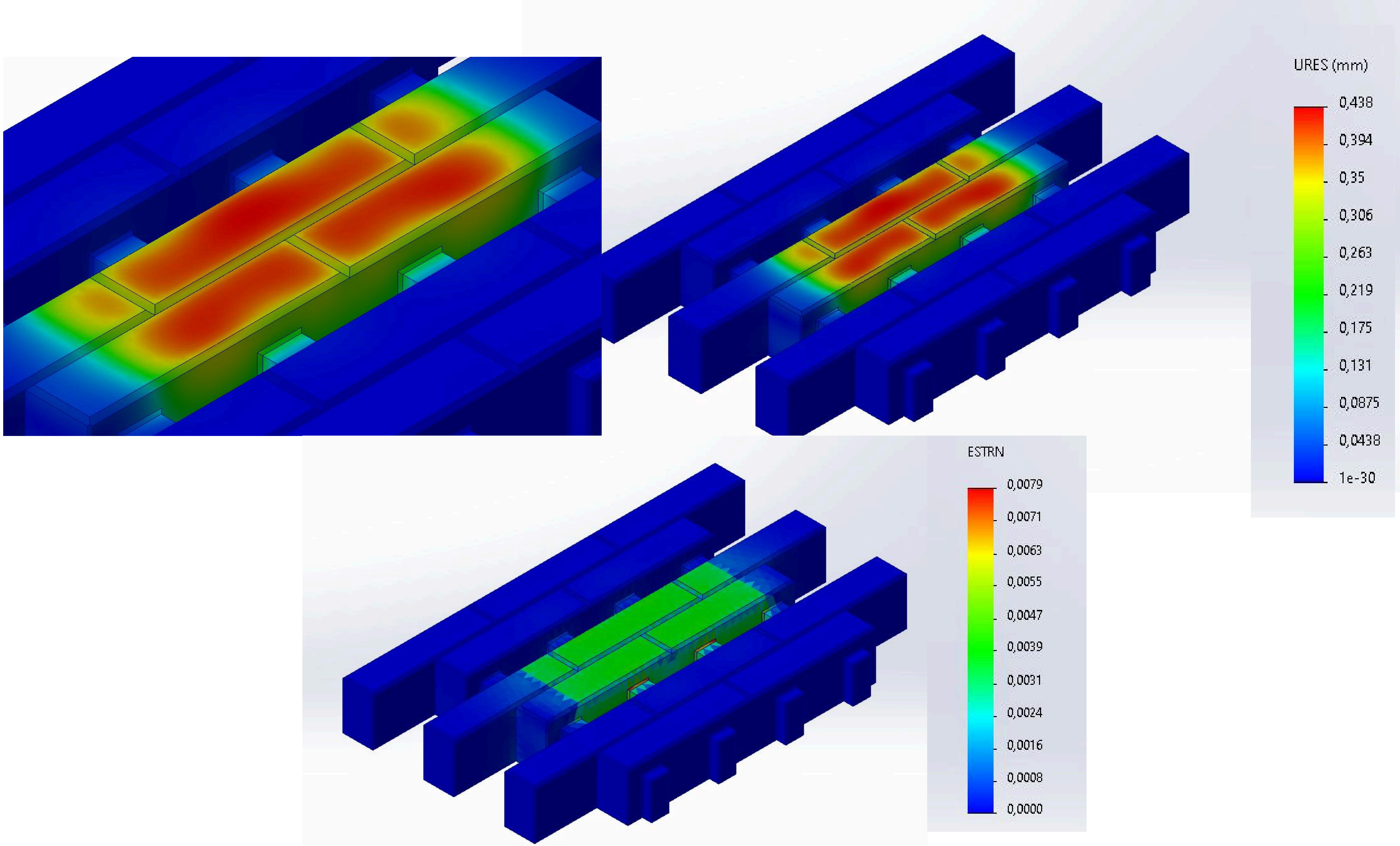


Figure 100: Strain and deformation analysis from FEA

8.2.3 Conclusion

The goal of the Finite Element Analysis (FEA) was to analyse the effect of a heavy truck parking on a CoRnGrid module. Modeling a force of 110362.5 Newton on an effective area of 24846.69 mm^2 resulted in a maximum stress of 8.73 MPa, approximately three times lower than the Yield Strength of PMP-CoRncrete. The highest stress value occurred in the transition area from the brick-body to the spacers. Additionally, a maximum deformation of 0.438 mm was observed on the top surface of the module. CoRnGrid can resist the load created by a heavy truck with 9000 kilograms per axis parked on top.

Though this digital model proved no failure would occur when CoRnGrid is loaded with a heavy truck, the design is not optimised for minimal material, though this would have sustainable benefits. This is done as the modeled load underestimates the movement of trucks and other vehicles on pavement. Future studies can use these dimensions as a starting point for optimisation.

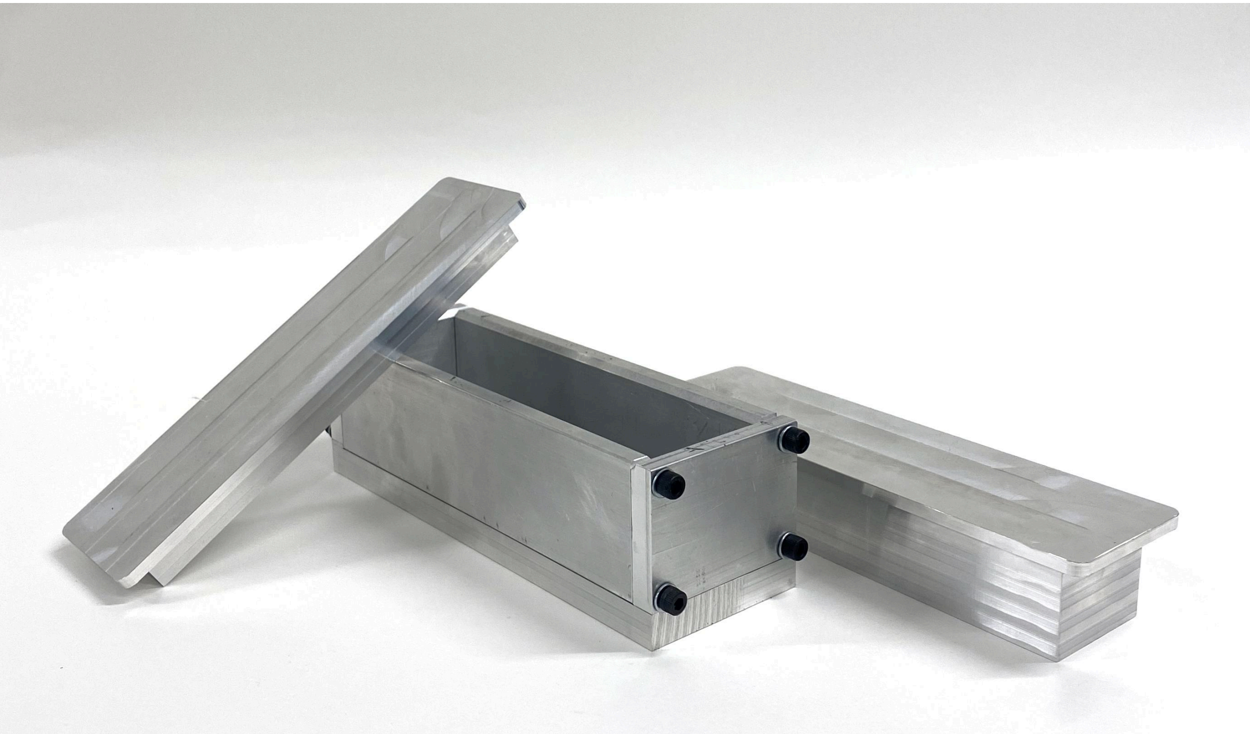
8.3 The brick

PMP-CoRncrete Grid Pavement is scaled to a physical model called 'the brick'. The brick is a PMP-CoRncrete shape measuring 192 by 48 by 40 mm (L x W x H) representing the shape of an ordinary brick, while meeting the extremes of lab facilities. Dimensions were limited by the maximum force of the hydraulic press as well as the maximum opening between the press plates. This model conveys the user experience of CoRncrete Grid Pavement through its associative shape, allowing exploration of its tactile features and perceived user experience, creating an interactive model to increase awareness and acceptation of CoRncrete. Additionally, the brick is an example of the scalability of CoRncrete manufacturing, being the largest volume ever produced in research. A mould specifically designed for CoRncrete manufacturing shows the possibilities of shaping in the hydraulic press.

To create the brick shape, a 5 part aluminium mould is used. This reduced the need for milling large pieces of aluminium, reducing the costs and time necessary. Additionally, it could improve the demoulding time. Aluminium was used as it was readily available and previous tinkering showed it to be a feasible mould material though it got damaged through the hardness of the sand grains.

As the pulverisation step was the least optimised for small sample manufacturing, it can be expected to become increasingly tedious and time-intensive when manufacturing these bricks. Additionally, the mould is heavier and and bigger, meaning increased resistance when stuck compared to the previous hydraulic press mould. Scaling CoRncrete to this size might produce cracks due to uneven hydration levels.

Due to lab capacity, no brick model could be made to include in the report, however, bricks will be presented during the graduation ceremony.



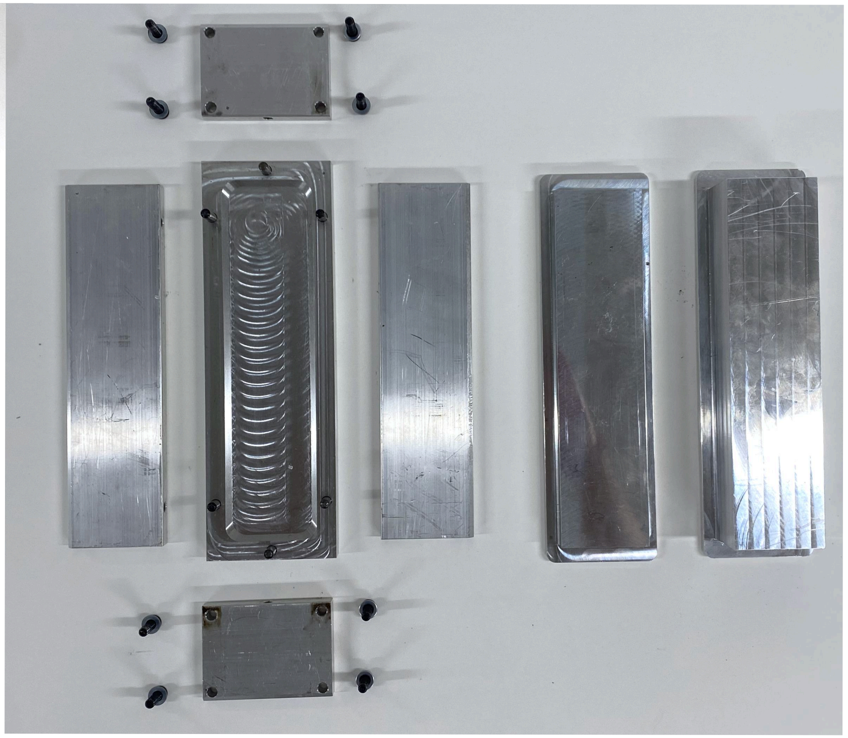


Figure 101: Brick Mould

9 conclusion

What is the purpose of this study?
What are the findings of this study?
What are the implications of these findings?
Which limitations influenced these findings?
Which areas of this study require further research?

Grid Pavement can improve urban areas through reduced Urban Flooding and battling the Urban Heat Island Effect, by integrating vegetation into infrastructure. Current Grid Pavement is made from concrete or plastic, affecting the climate. The goal of this research was to find an alternative material with an improved sustainable performance for Grid Pavement called TAWWA GreenGrids, developed by Tonn.

CoRncrete consists of water, sand and starch, making it a cost-effective, non-toxic, non-contaminating material partly from renewable sources. Its manufacturing process is low-tech, energy efficient and allows for fast prototyping, while producing samples with an Ultimate Compressive Strength of up to 91.7 MPa, with the inclusion of additives. This material is based on binding sand through a complex multi-factor process called starch gelatinisation, where the rate of gelatinisation improves structural qualities.

This researched aimed to holistically develop CoRncrete by analysing technical as well as human-centered aspects. This study gathered data regarding CoRncrete components and manufacturing processes to improve the scalability, quality and sustainability of the material. A technical analysis was performed to identify and compare the mechanical properties of CoRncrete with different compositions. Additionally, this study identified the experiential characteristics of CoRncrete manufactured with three different sand grain sizes. The technical and experiential characteristics are concluded in a Grid Pavement (GP) design that is feasible and desirable.

CoRncrete containing sand grains measuring 0.250 - 0.500 mm allows for homogeneous incorporation of water and creates a pourable wet mixture, likely reducing mixing times while improving material transfer and scaled production quality. The oven allows for large scale gelatinisation to create a high volumes of gelatinised mixtures. Grinding the mixture, rehydrating and forming the product through compression can be done at industrial scale, while grinding, and compression forming can be done at large volumes and high speeds at industrial scales.

Manufacturing CoRncrete with sand grains measuring 0.250 - 0.500 mm resulted in a smooth and compacted final sample. Forming CoRncrete in the hydraulic press creates the highest quality material, creating a solid surface without deformations provided the optimised manufacturing protocol is followed.

While manufacturing CoRncrete in the microwave is the most energy efficient, oven manufacturing is the most energy intensive. Separating the gelatinisation and forming phase reduces the oven time, improving the energy required for gelatinisation while hydraulic press forming requires a negligible amount of energy.

Experiential characteristics of CoRncrete with varying components was studies through interviews. CoRncrete manufactured with sand grains of 0.250 to 0.500 and 0.500 to 1.000 mm, respectively, promotes a recognisable, ordinary and natural appearance, while sand grains of 0.125 to 0.250 mm promote a mysterious and confusing experience. Visible sand grains are likely the contributor the recognisable, ordinary and natural appearance and provide a fascinating tactile experience that invites curiosity and attraction, though it can induce skepticism regarding material strength. CoRncrete with 0.250 to 0.500 mm sand grains is likely most suitable for GP as it balances novelty and recognisability and adds an organic perception to the material, providing a perceived sustainable competitive advantage to current GP materials.

From compressive testing could be concluded that curing time after press forming substantially affected the Ultimate Compressive Strength (UCS), while cracks have no direct negative effect. Next to gelatinisation, curing time might be the most important process to affect the structure of CoRncrete. On average, incorporating potato starch resulted in CoRncrete with a higher compressive strength, compared to cornstarch. The UCS of cornstarch-containing samples correlated positively with a decreased sand grain size, while the UCS of potato starch-containing samples did not, examplifying the complex multi-factor character of gelatinisation. Samples manufactured in the oven have a twice lower UCS than their hydraulic pressed counterparts. CoRncrete containing 0.125 to 0.250 mm sand grains and cornstarch and CoRncrete containing sand grains of 0.250 to 0.500 mm and potato starch were the two CoRncrete compositions with the highest mechanical properties. Due to the scalability and experiential advantages, CoRncrete for Grid Pavement is considered most suitable containing potato starch and sand grains measuring 0.250 to 0.500 mm.

Combining these results led to a final concept design for Grid Pavement manufactured from CoRncrete. CoRncrete formed in the hydraulic press, containing potato starch and 0.250 to 0.500 mm sand, called PMP-CoRncrete, can likely be scaled to industrial volumes while producing high-quality products with sustainable potential. PMP-CoRncrete provided a desirable user experience and satisfying mechanical characteristics. The Grid Pavement is designed with the vision to transform the public space by seamlessly integrating vegetation into infrastructure, creating harmonious urban areas. The familiar appearance of CoRncrete improves acceptance of the novel material, while curiosity and excitement is induced by the unique texture. Each Grid Pavement module measures 600 by 390 by 80 mm, weighs 23.26 kilograms and costs €12 to €15. The design is compatible with conventional Dutch pavement bricks, while integrating vegetation into infrastructure harmoniously and providing additional grip. The size of the modules optimises transportation and installation, while the reversible connections provide sustainable opportunities. The design is validated through a Finite Element Analysis showing no destructive deformations and stresses caused by a static load resembling a truck wheel with 4500 kilograms on top, including a safety factor of 2.5.

These results suggest that CoRncrete is technically feasible to resist traffic, while adding to a desirable user experience and potentially improving the sustainability of Grid Pavement.

Limitations

It was assumed that developing a material for Tonn would be seen as the most desirable to improve the sustainability of their TAWWA GreenGrids Grid Pavement. This would make Tonn a material producer next to a Grid Pavement producer, while the company does not currently contain the workforce and skills necessary. This approach makes the redesigned Grid Pavement more future oriented rather than immediately feasible and viable.

This research was performed by one Master Graduate student of Industrial Design Engineering at the TU Delft, limiting material science and pavement expertise. For example, analysing the micro-structures, as done in previous CoRncrete research, can allow for additional insights that could alter the conclusions of this research. Additionally, a limited amount of samples could be manufactured and manufacturing and testing was limited to Lab Settings.

Due to time constraints, CoRncrete was developed with limited depth. Improving the water resistance of CoRncrete required an extensive investigation on additives which was deemed too extensive for this research. Additionally, the implications of each additive on the sustainability of CoRncrete would have required a large-scale Life Cycle Assessment to understand the trade-off between functionality and sustainability. Adding a waterproof coating, as proposed in previous CoRncrete research, is deemed futile due to the abrasion caused by traffic on Grid Pavement.

Technical aspects of Grid Pavement were simplified to represent a static loads rather than reflect the strict requirements and norms set for traffic loaded infrastructure. Norms regarding for example skidding and long-term durability should be considered before large-scale implementation of CoRncrete Grid Pavement can become feasible.

The Grid Pavement design is optimised to enhance the material characteristics while being technically feasible. Accessibility of Grid Pavement and vegetational management and sustainable vegetation optimisation were not researched, but crucial for successful implementation of CoRncrete GP.

Future studies

CoRncrete

Future research should aim to improve the water resistance of CoRncrete while simultaneously identifying applications where limited water resistance poses opportunities for CoRncrete. Creating a hydrophobic or water resistant material from within would make coatings obsolete and allows for intensive use of CoRncrete in abrasion sensitive applications. Adding waterproofing during rehydration or hydraulic press forming might introduce new additives as no heat is added after these phases.

A Life-cycle-assessment should be used for scaling CoRncrete manufacturing and selecting waterproofing additives, ensuring holistic sustainable development. Each additive has its own respective effect on the environment, while introducing new or improved material characteristics, creating a trade-off between functionality and sustainability.

Optimising the curing time can further improve the mechanical properties of CoRncrete. The processes in the micro-structure of CoRncrete during curing should be researched to better understand one of the most important processes of CoRncrete manufacturing.

Further improving CoRncrete sustainability might be done through combining hydraulic press forming with microwave gelatinisation. Challenges will likely arise in scaling and pressure build-up caused by the rapid internal temperature increase.

As microwave CoRncrete manufacturing does not create toxic or polluting waste-products and uses abundant resources to create a material with good strength properties, low resource settings might benefit from local implementation. Additionally, microwave manufacturing is energy-efficient and does not require fossil fuels.

Further investigating pigmentation opportunities can increase the versatility of the user experience of CoRncrete, introducing additional application opportunities.

Future studies are currently conducted in the TU Delft Industrial Design Engineering Bachelor course Materials and Manufacturing. Multiple student groups investigate additives and manufacturing processes and identify technical and experiential aspects to design desirable and feasible products for new application areas.
Through discussions with professors and students, these groups focus on sustainable pigmentation, waterproofing, shaping and acoustic qualities of CoRncrete, among other material properties. As initially speculated by participant 6 of the experiential interviews, one study group are researching the reversibility of CoRncrete's gelatinisation process through joining and repairing.

Grid pavement

The goal of Grid Pavement is to combine vegetation with infrastructure to combat the Urban Heat Island (UHI) effect and Urban Flooding (UF). To assess the effect of CoRnGrid on UHI's and UF, full scale application and data gathering would be most optimal. However, lab settings simulating weather and would be the first steps. Climate adaptive data should be produced to justify design choices.

Designing durable CoRncrete Grid Pavement requires waterproofing. To implement CoRncrete in Grid Pavement as soon as possible, a coating can be applied, where Mansour et al. (2020) identified pure beeswax, paraffin wax, and tristearin as most effective. This would likely require frequent re-application due to abrasion caused by traffic.

Alternatively, Grid Pavement could be redesigned for near-future implementation by collaborating with a material producer. This would reduce the responsibilities for material development within Tonn, allowing a focus on the design features to accommodate a sustainable, desirable and accessible design.

Attaining certification would increase acceptance and would very likely result in the implementation of CoRncrete as a sustainable alternative for Grid Pavement.

As Grid Pavement is largely implemented in parking lots, accessibility for all people should be considered. A desirable interaction with Grid Pavement produces positive emotions regarding Grid Pavement as well as the material. Future studies should include users from varied backgrounds to understand the perception and use of Grid Pavement.

Installation processes should be optimised to ensure correct implementation of CoRncrete Grid Pavement. Involving municipal management and construction companies is crucial to design the installation according to the requirements and wishes of relevant stakeholders.

Researching the optimal sustainability, management and social contribution of vegetation of Grid Pavement could increase the social and sustainable value, likely improving acceptation and implementation. Vegetation should not be limited to grass as value can be added through the inclusion of varying vegetation in different contexts of application. Including ecologists and municipal management can improve management and the social and sustainable value of Grid Pavement vegetation.

Finally,

While future trade-offs between functionality and sustainability should ensure the durability of CoRncrete proves to be technically apt while adding an enhanced user experience and promising sustainable aspects to Grid Pavement design.

Reflection

After 6 months, this project is almost over. Reflection helps to learn from experiences and helps refine the designer and engineer that I will soon officially become.

First I want to talk about material science. Before this project I never understood Stress-Strain curves. I was not really sure what bio-based means (though I am still uncertain). And I defititinely never heard of CoRncrete. Starting this project felt like a whole new sub-study, with new scientific knowledge and business opportunities. Through The Green Village and my supervisors I gained a lot of insights from various perspectives. I felt like a sponge taking it all up. Until I had to do it myself. Tinkering sounded very free and gave me the opportunity to start exploring CoRncrete. However, it soon became a maze with endless options . Due to my inexperience I did not know how much variables I should start testing or even which test setup worked best. Manufacturing samples and performing tests felt like I knew everything I had to, while in hindsight I had forgotten multiple steps. It is probably very normal to go through this cycle when learning something new and I am very happy I took this challenge.

Second I would like to talk about my supervisors. Meeting every week seemed like a busy schedule, but after every meeting I got new input and new energy. It felt like we always talked in opportunities, doing more. I enjoyed being pushed throughout this project, never sitting still, barely cutting corners. However, it might not always be the best thing for me to be pushed as I am ambitious myself already. The project ends while I am just getting started. Things are falling into place and I am starting to understand materials and methods. Therefore I am happy that finalisation is at hand. The knowledge is collected and the next person can continue.

Third I would like to reflect on my changed perspective. Getting to know more about materials and sustainability has not clarified much. One thing I know for sure is that innovation is slow if you want it to be. Complex governing bodies and regulations and norms make a lot of innovations difficult to implement on a large scale. When you are inside the university ‘bubble’, everything seems possible and almost everyone thinks towards a better future. While innovation is held back, I see it as a challenge to become a young professional with a voice to make an actual change, right now.

That leads to my last point. Before this project I was considering designing in low-resource settings as a future career. It makes an impact, but there is a lot of uncertainty. During this project I have began to appreciate more low-resource solutions in high-resource settings. Using cow dung in construction shows how simple material science can be. Sometimes you do not need to look at future technologies, but dig back into old knowledge. In biomimicry you look at nature for inspiration. Why not look back at ourselves and ask how did we solve this without plastics. We survived long enough to make it here. Why lose all that knowledge by only going forward? In the near future I would like to start a job designing climate adaptive cities. Possibly inspired by old technologies.

To conclude, this project pulled me into the world of material science and sustainable materialisation. At the same time I gained knowledge in the urban planning sector. This load of new knowledge made this graduation rather intense, but very educational.