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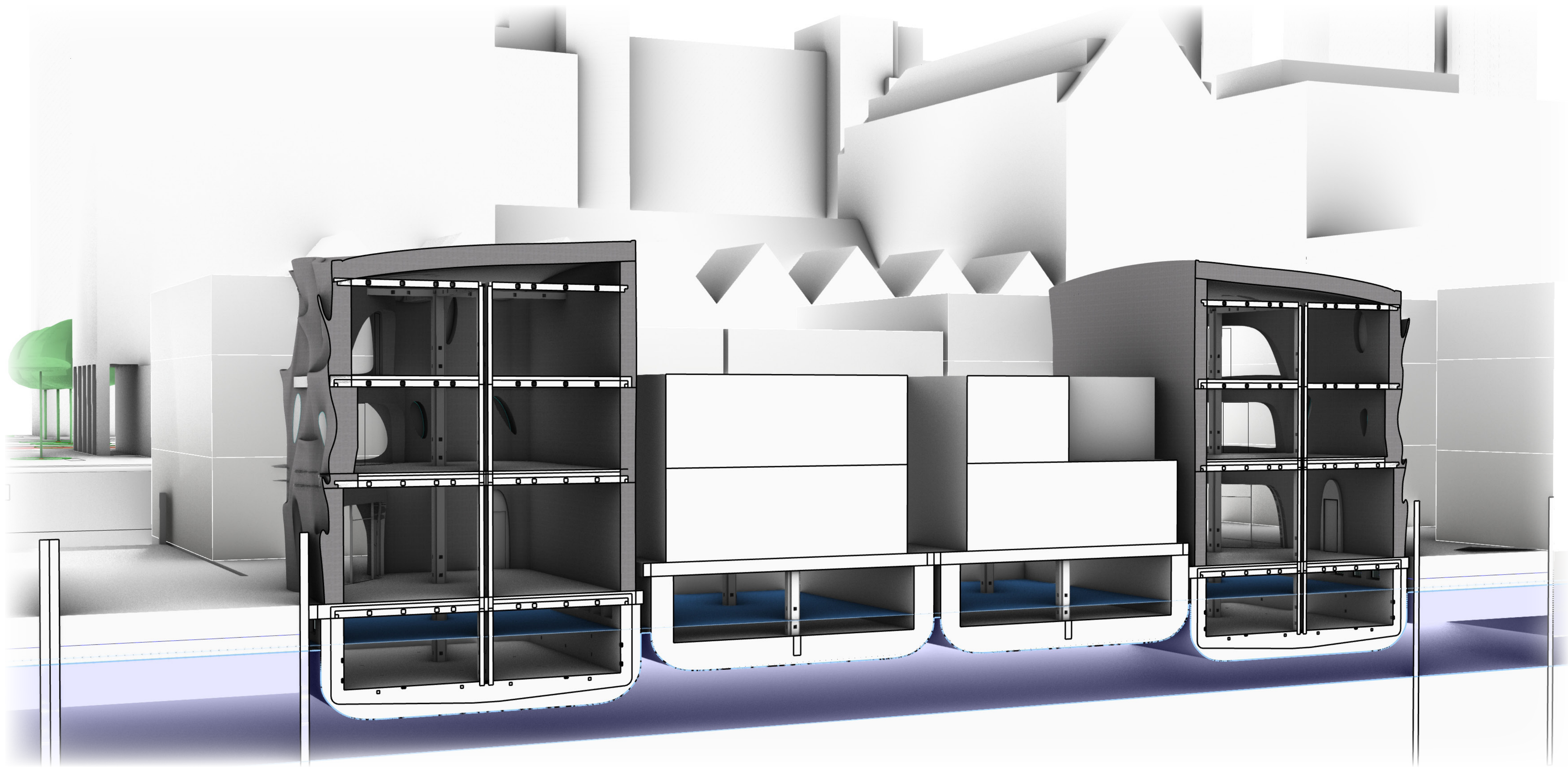

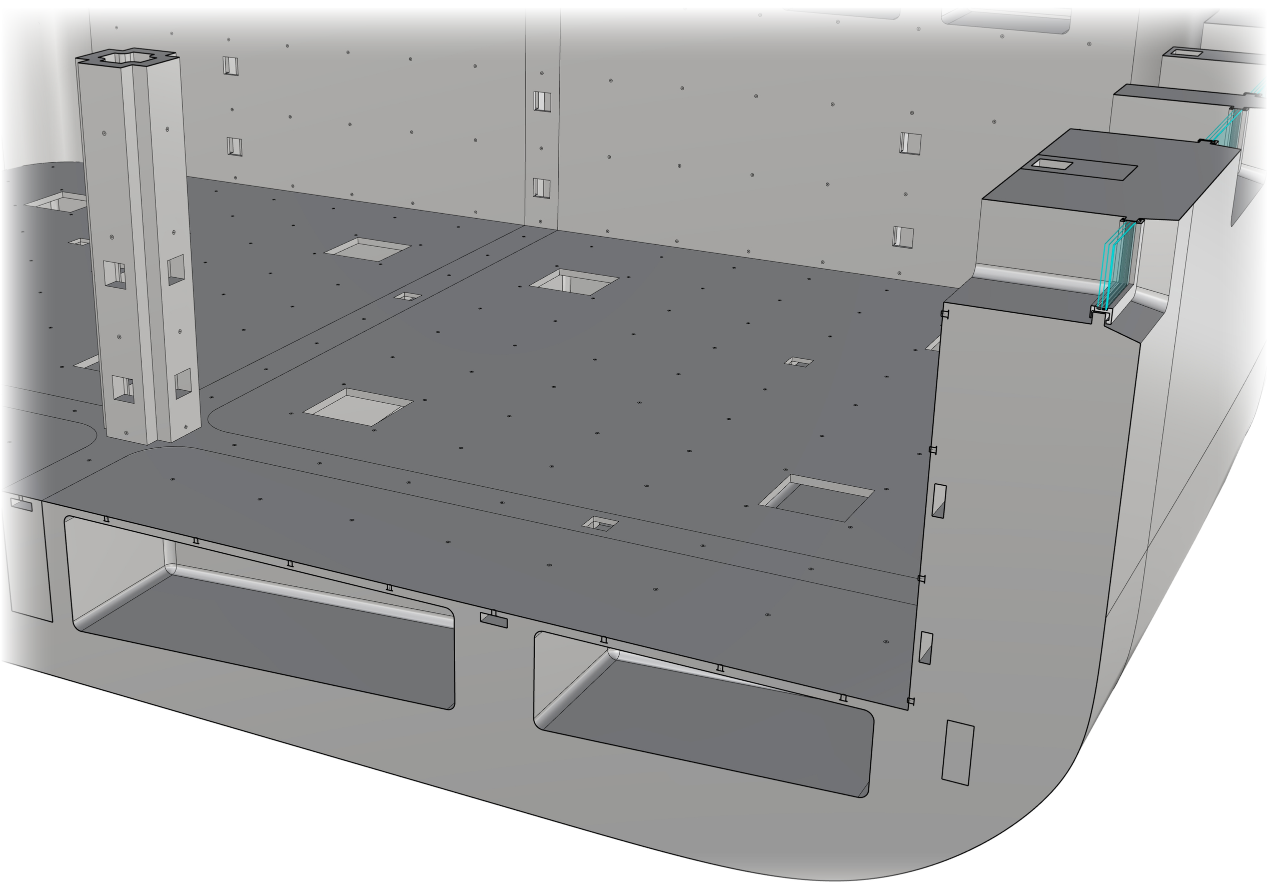

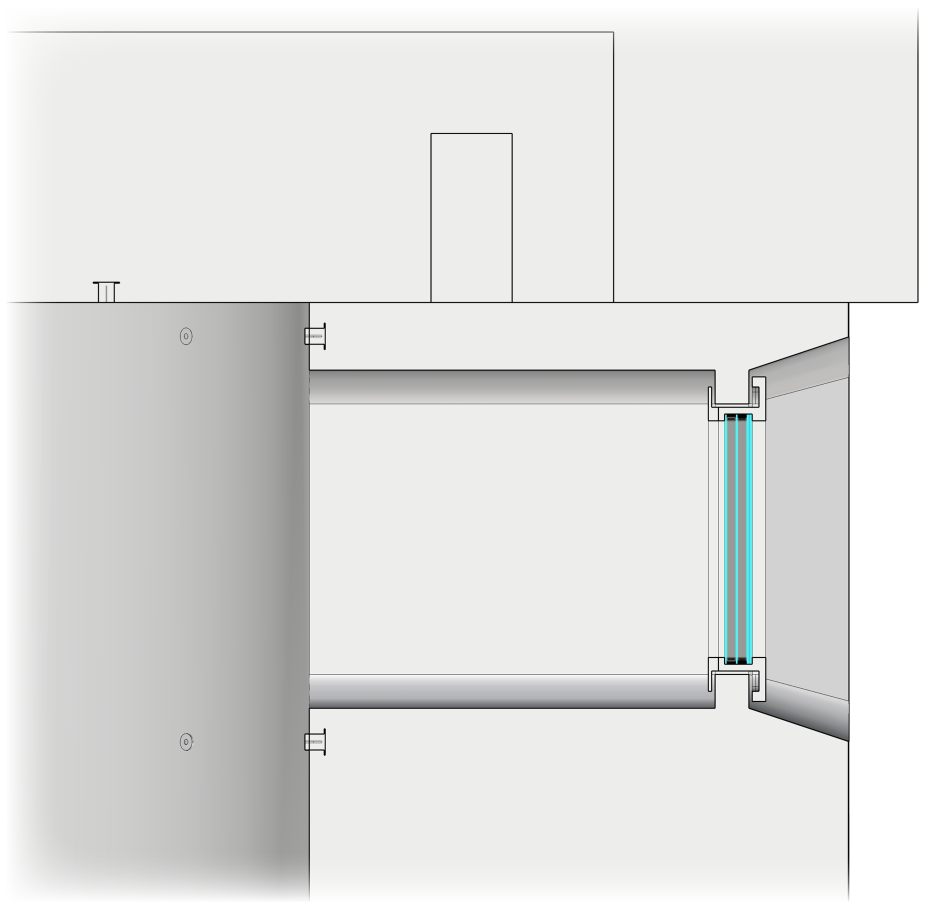

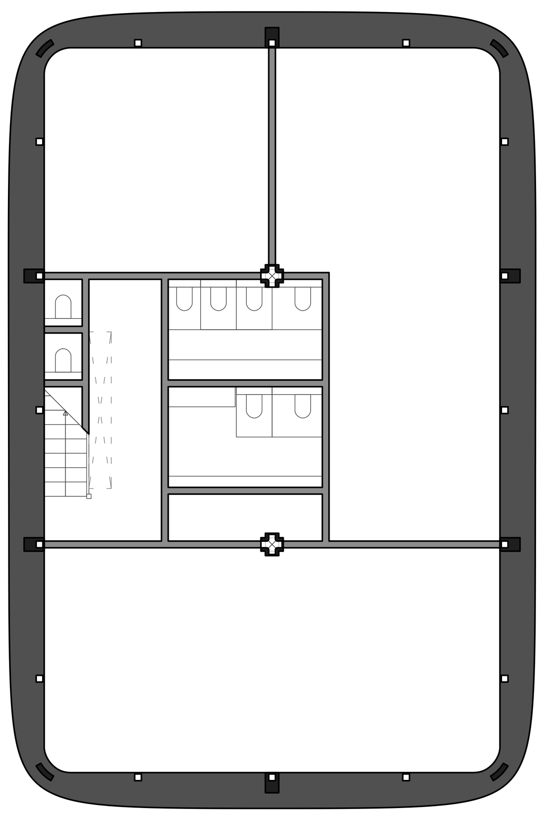

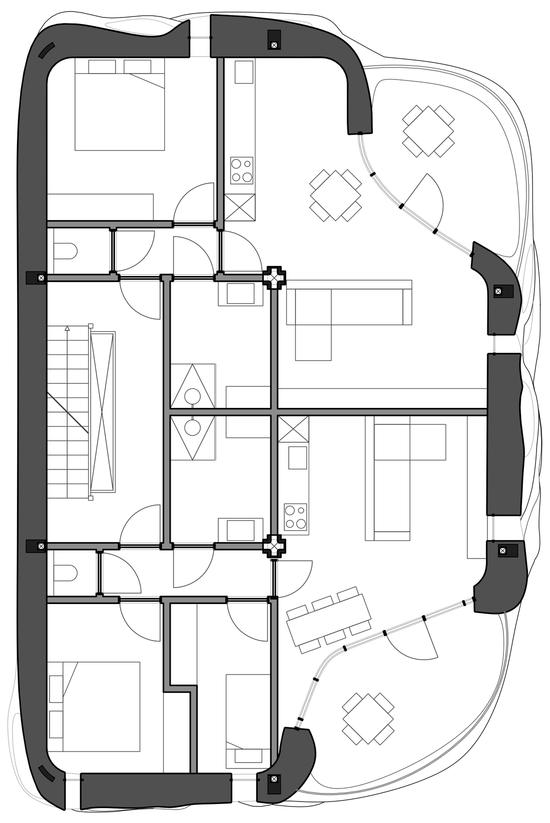

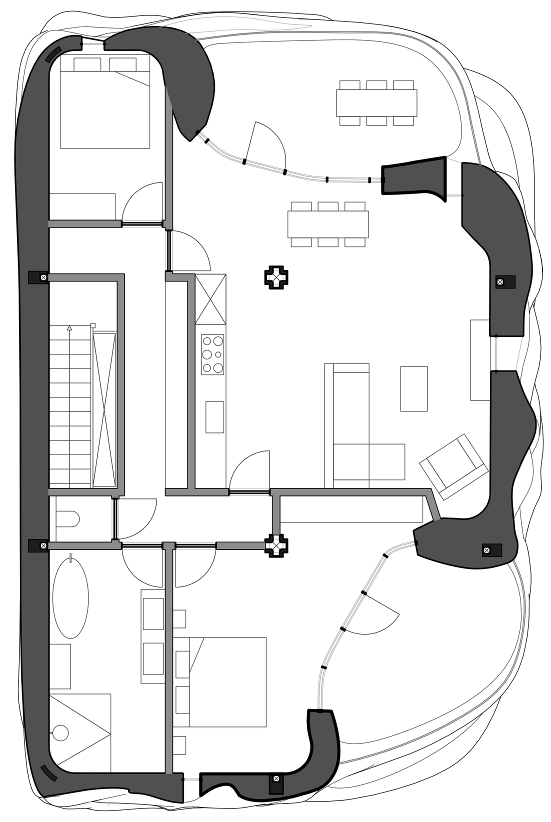

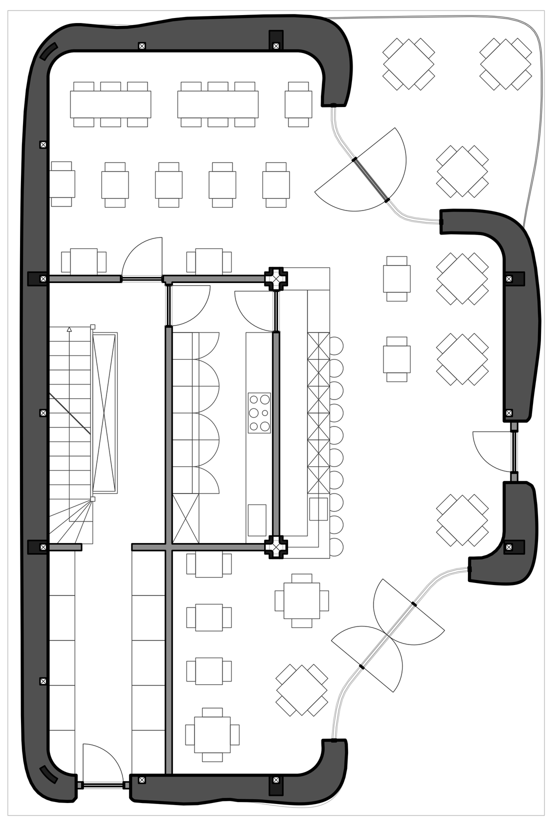

Graduation report

Sam Meeuwis - 4441397

2-4-2026

Table of content

Graduation Plan

Personal information		
Name	Sam Jacob Ferdinand Meeuwis	
Student number	4441397	
Studio		
Name / Theme	Architectural Engineering	
Main mentor	Stephan Verkuijlen	*Architectural Engineering + Technology*
Second mentor	Mauro Overend	*Architectural Engineering + Technology*
Argumentation of choice of the studio	A deep fascination for how material characteristics can influence their architectural use and expression through engineering innovation, with a strong focus on prevalent issues in the Dutch architectural and build environment.	

Graduation project
Title: Dutch Waste to Circular structure: a holistic overview for Geopolymers in the Dutch context.
Goal
Conventional concrete has a mayor environmental impact: It is a leading contributor to global CO_2 emissions due to its chemistry and energy intensive global production process. On top of that it exhausts non-renewable resources. Furthermore the life-cycle of the build environment is far from self-sustaining and a unclosed loop, resulting in loss of qualitive re-use possibilities. By answering the research question: **How can geopolymer concrete synthesized from Dutch industrial and construction waste streams be positioned as a circular building material, in comparison to Portland cement-based concrete and UHPC?** The research aims qualify, validify and benchmark a geopolymer concrete derived from Dutch waste streams against conventional concrete(s). It maps out the flows and possibilities to bridge the gap between material innovation and research. providing engineering insight and design applications for the development of architectural elements, structural and/or non-structural within a Dutch context. Answering the questions: 1) What Dutch waste or residual materials are suitable as geopolymer precursors or aggregates, and in what quantities and quality are they available within the Netherlands? 2) What are the key environmental and mechanical differences between normal concrete, UHPC, and geopolymers? 3) How can design strategies leverage the specific characteristics of regionally developed geopolymers? The research culminates the richness of possibilities through the use of geopolymer based components in the design of a prefabricated elements for an adaptational mixed-use building block, located in the Spoorweghaven in Rotterdam. Making use of regional sources within a semi aquatic design site, showcasing engineering innovation.
Process
Method description
• Literature Review: On geopolymer chemistry, mechanical performance, and environmental benchmarks of geopolymers, OPC and UHPC. • Material Mapping: Identification and documentation of relevant Dutch waste streams

- Renewi Collaboration: Scheduled site visit and interview with Renewi to assess the practical availability, processing, and future potential of recycled granulates for geopolymers.
- Interviews: depth interviews with a broad spectrum of experts both academically and in the field will be held to further clarify material specific topics and to precisely gather and assess data.
- Comparative Analysis: Using collected data to compare geopolymer compositions with standard UHPC mixes in terms of strength, workability, shrinkage, and lifecycle impact.
- Practice-based Learning: Participation in the RILEM PhD Training Course (May 2025, TU Delft), with practical modules on geopolymer production, structural behavior, and design integration.
- Schematic Modelling: Infographic development showing the material cycle, synthesis flow, and benchmark relationships.

Literature and general practical preference

Scientific and Technical Literature:

- Duxson et al. (2007) – Role of inorganic polymers in sustainable materials
- Provis & van Deventer (2009) – Geopolymers: Structures and Applications
- Li et al. (2020) – Durability of Ultra-High Performance Concrete
- Skariah et al. (2022) – Geopolymer concrete with recycled aggregates
- Adjei et al. (2022) – Geopolymer binders in oil well cementing
- Davidovits (2020) – Geopolymer Science and Technology
- Tran et al. (2025) – UHPC mixtures using waste materials
- Various papers and slides provided in the Rilem Training course lectures.

Practical References and Data Sources:

- Joostdevree.nl – Concrete types and strength classes
- Renewi – Dutch circular waste processing (site visit and collaboration)
- RILEM Course (TU Delft, 2025) – Experimental geopolymer methods and applications
- Previous AE Studio material research projects and precedent studies
- Interviews with experts from academic world and from practice

Reflection

This graduation project intertwines all three of the Architectural Engineering studio's pillars: Flow Stock and Make. Regional flows are combined using the existing build environment stock as a resource. Engineering details and material characteristics showcase the making potential and innovation within a challenging engineering design-location. Showcasing the different scales within architecture and bridging the gap between the academic world and innovative application within the research, design, and engineering fields.

Socially, this project contributes to the urgent need for climate-conscious and circular construction strategies. Professionally, it explores new pathways for implementing underused waste streams into building practice. Scientifically, it addresses knowledge gaps in the practical and architectural application of geopolymer concrete, to aid in future standardization and adoption. The project acts as a bridge between research, material innovation, and design—advancing the innovative discourse on sustainable construction.

Research plan

From Dutch Waste to Circular Structure:

Exploring the potential of geopolymers as locally sourced Dutch building materials, benchmarked against Ultra-High Performance Concrete and critically compared to conventional Portland Cement Concrete

TU Delft – Faculty of Architecture and the Built Environment
Architectural Engineering Graduation Studio – Research Plan

Student: Sam Jacob Ferdinand Meeuwis
Student number: 4441397

Design Tutor: Stephan Verkuijlen
Research Tutor: Mauro Overend
Date: 06/05/2025

Argumentation of Choice:

The selection of this topic arises from a longstanding fascination with materials, their lifecycles, and how they shape the built environment over time. In particular, the durability, long-term value, and potential for circular flows of materials have formed the foundation of this research. This aligns with an increasing urgency within the architectural engineering field to develop and apply environmentally responsible building materials. The choice to investigate geopolymers is driven by their seemingly obvious potential to significantly reduce carbon emissions and promote circular material flows within the construction sector. As a student in the AE Studio, I aim to investigate the potential of a tailored geopolymer for the Dutch context from waste flows and circular design as starting point. the findings from this research will used as the main integrational aspects of my design process.

I am particularly drawn to concrete for its versatility as a construction material, the widespread use, and it's applicability within almost all building sectors. Throughout this project, I seek to understand how geopolymer alternatives can inform and inspire new forms of architectural expression and structural logic.

Geopolymers show promising properties for innovation in the concrete sector, due to their unique performance: fresh properties, strength development, volume stability, structural behaviour, durability, time dependant properties. All of which are usefull key aspects to making durable, circular concrete. Unfortunately nowadays there are still no applicable design codes or norms for this material class and no standards in the construction industry.

The integration of industry collaboration and advanced academic insight from practical and expert academic background provides a unique foundation for design-relevant material research. Bridging the gap between innovative research and practical implementation possibilities.

Problem statement, hypothesis & relevance

Problem Statement:

Cement-based concrete, particularly Portland cement, is a major contributor to global CO_2 emissions, largely due to the energy-intensive clinker production process and the extensive use of non-renewable resources (Duxson et al., 2007). Although interest in alternative binders is growing, few options have proven to be both scalable and practical for widespread implementation (Adjei et al., 2022). Among the most promising candidates are geopolymers, especially when derived from regionally available waste materials, offering significant environmental advantages and potential reductions in carbon emissions (Skariah et al., 2022).

Direct comparison between geopolymers and conventional Portland cement concrete is, however, problematic. The disparities in market maturity, economic modelling, and performance expectations can lead to skewed or inconclusive evaluations. To create a fair and functionally relevant point of reference, this study benchmarks the performance of geopolymer-based materials against Ultra-High Performance Concrete (UHPC), a technologically advanced but still cement-based material with high structural and durability metrics (Li et al., 2020; Tran et al., 2025).

This research aims to address this disconnect by mapping and evaluating Dutch waste-derived materials suitable for geopolymer synthesis and establishing a comparative framework that assesses their potential in relation to OPC and UHPC. This framework will support a more well-informed architectural integration of these materials, helping to address the current lack of formal design standards for geopolymer-based construction, helping the push for innovation.

Hypothesis:

Dutch industrial and construction waste streams can be refined and used into consistent, qualitively and quantitively precursor materials for geopolymer synthesis to develop a structural and environmentally superior concrete alternative.

Design Relevance:

The technical findings from this study will not remain abstract. They directly feed into the design process of the AE Studio by informing material-driven design strategies. The material will not only need to meet performance benchmarks set by UHPC but can also allow more regionally adapted and circular architectural applications than normal concrete. This includes how geopolymer properties can influence geometry, assembly logic, and performance within Dutch urban typologies. Finding key insights from material knowledge to input in an innovative design solution will showcase the potential of the material and the influence the designer has to make it an economically viable and useable solution.

Glossary (Key Terms)

- **Aggregate**: Granular materials used in concrete mixtures that provide bulk, strength, and stability. Aggregates are typically classified as fine (sand) or coarse (gravel, crushed stone) and make up roughly 60–80% of the concrete's volume. Their shape, size, and composition greatly influence the workability, durability, and strength of concrete. In sustainable practices, recycled aggregates from construction and demolition waste are increasingly explored as alternatives to natural aggregates.
- **Concrete (C)**: A construction material consisting primarily of water, cement (most often Portland cement), aggregates (such as gravel, sand, or crushed stone), and optional additives. The abbreviation "C" is commonly used to refer to normal concrete, e.g., C20/25 indicates a compressive strength of 20 MPa (cylinder) and 25 MPa (cube), for Portland cement concrete the abbreviation PCC can be used. Concrete is distinguished from UHPC by its higher water-to-cement ratio, lower strength, and greater variability in composition. For standard applications in building and infrastructure, conventional concrete remains the most widely used material worldwide (Joostdevree.nl, 2024).
- **Geopolymer**: A class of inorganic binders formed through the alkali activation of alumino-silicate-rich materials—often derived from industrial or post-consumer waste. While commonly referred to as 'geopolymers,' the terminology is widely debated within the scientific community due to overlapping definitions and inconsistencies in chemical classification (Provis & van Deventer, 2009). Some researchers reserve the term for systems that result in specific polymeric frameworks, as advocated by the Geopolymer Institute (Davidovits, 2020), while others use it more broadly to include any alkali-activated materials (AAMs). For the purposes of this research, the term 'geopolymer' is adopted in its broadest sense, to reflect the architectural potential of various alkali-activated waste-based binders without restricting the investigation to a narrow typological category.
- **Precursor**: A raw or processed material that contributes to the chemical formation of a binder, such as fly ash or metakaolin.
- **UHPC (Ultra-High Performance Concrete)**: Ultra-High Performance Concrete (UHPC) is a dense, high-strength cementitious composite material characterized by its extremely low porosity and high compressive and tensile strength. It is based on a Portland cement binder system, enhanced with supplementary materials like silica

fume and finely graded quartz sand. UHPC typically includes a low water-to-binder ratio and steel or organic fibers, which contribute to its superior durability and structural performance (Li et al., 2020). With compressive strengths exceeding 150 MPa and a highly refined microstructure, UHPC resists chemical attack, abrasion, and freeze-thaw cycles better than conventional concrete. Due to its cost and precision requirements, UHPC is often used in infrastructure elements like bridges, façade panels, and thin-shell structures where performance and longevity are critical.

Research Question & Methods

Research Question:

How can geopolymer concrete synthesized from Dutch industrial and construction waste streams be positioned as a circular building material, in comparison to Portland cement-based concrete and UHPC?

Sub-questions:

- What Dutch waste or residual materials are suitable as geopolymer precursors or aggregates, and in what quantities and quality are they available within the Netherlands?
- What are the key environmental and mechanical differences between normal concrete, UHPC, and geopolymers?
- How can design strategies leverage the specific characteristics of regionally developed geopolymers?

Research Methods:

- **Literature Review**: On geopolymer chemistry, mechanical performance, and environmental benchmarks of geopolymers and UHPC.
- **Material Mapping**: Identification and documentation of relevant Dutch waste streams (e.g. metakaolin, slag, recycled construction aggregate).
- **Renewi Collaboration**: Scheduled site visit and interview with Renewi to assess the practical availability, processing, and future potential of recycled granulates for geopolymers.
- **Interviews**: depth interviews with a broad spectrum of experts both academically and in the field will be held to further clarify material specific topics and to precisely gather and assess data.

- **Comparative Analysis**: Using collected data to compare geopolymer compositions with standard UHPC mixes in terms of strength, workability, shrinkage, and lifecycle impact.
- **Practice-based Learning**: Participation in the RILEM PhD Training Course (May 2025, TU Delft), with practical modules on geopolymer production, structural behavior, and design integration.
- **Schematic Modelling**: Infographic development showing the material cycle, synthesis flow, and benchmark relationships.

Method Table:

Sub-question	Research Activity	Source/Data	Tool/Approach
Suitable waste materials?	Material mapping, Interviews	Renewi site + LCA literature	Qualitative assessment, visual flow mapping
Differences with UHPC?	Literature + benchmarking	Academic databases, performance sheets	Comparative analysis matrix
Integration in design?	Diagramming + RILEM synthesis	Course content, design precedents	Typological mapping, AE design strategy framing

Timeline Overview

Detailed Research Timeline (Week 3.10–4.8):

Week	Activity
3.10	Continued literature synthesis, refining structure, start data collection
4.1	Material data analysis, initial framework drafting
4.2	Renewi preparation, ongoing comparison modeling
4.3	Renewi site visit + post-visit documentation; Preparation for RILEM course
4.4	RILEM PhD Training Course (May 12–16, TU Delft)
4.5	Post-RILEM documentation and processing of insights
4.6	Visual modelling, Sankey diagram, typological concepts
4.7	Thematic paper writing and revision
4.8	Final editing + P2 presentation prep

Parallel Processes: Literature reading, diagram development, and comparative matrix construction run continuously in parallel with the main timeline.

Global Timeline:

- **Phase 1: Research Foundation** → Material discovery, field input, academic deepening
- **Phase 2: Technical Synthesis** → Benchmark construction, modeling, and validation
- **Phase 3: Design Integration** → Post-P2 transition into architectural design experimentation for P3 and beyond, including the spatial application of the researched material. During this phase, a suitable project location will be selected based on proximity to relevant material sources and processing infrastructure. While Rotterdam is a logical candidate due to scale and circular ambitions, other local options remain open depending on research outcomes.

References

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Introduction photo graduation report collage

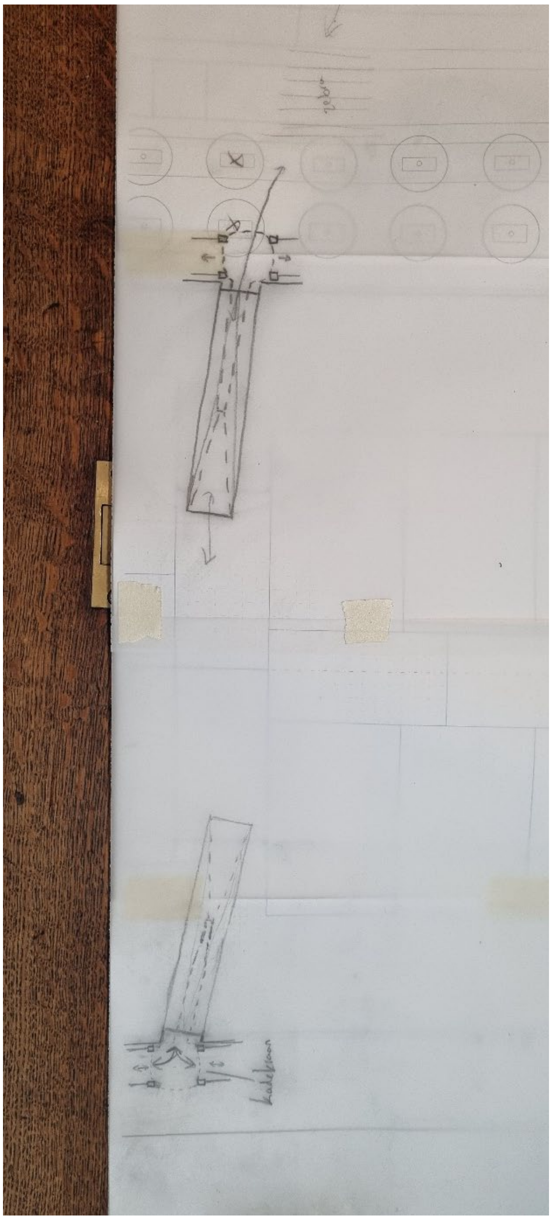
This project shows how my material research actively generated the architecture, rather than being applied afterward in a series of pictures.
Grounded in research on geopolymer concrete and Dutch waste streams , the design evolves as a continuous interaction between making, testing and reflecting.

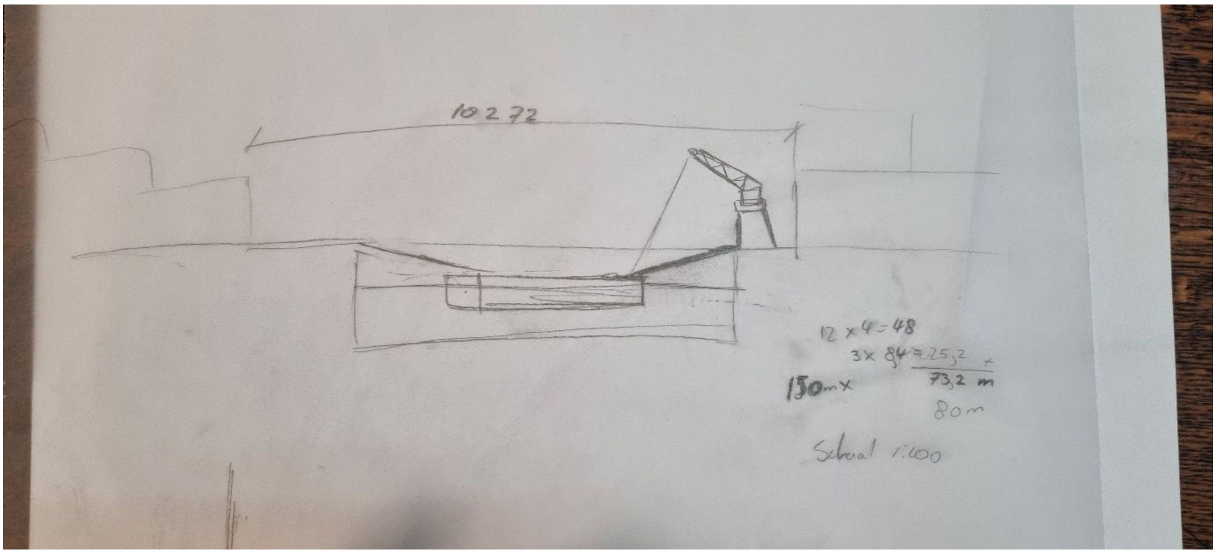
The project positions itself between:

- material innovation
- production logic
- urban system design

The outcome is not a fixed building, but a framework for change.
This report shows the process I went through from start to finish with iteration, subjects and themes broken up in a nonlinear and heavily reduces set of pictures of final results and processes in between.

It is followed by the reflection and subsequently my research paper.

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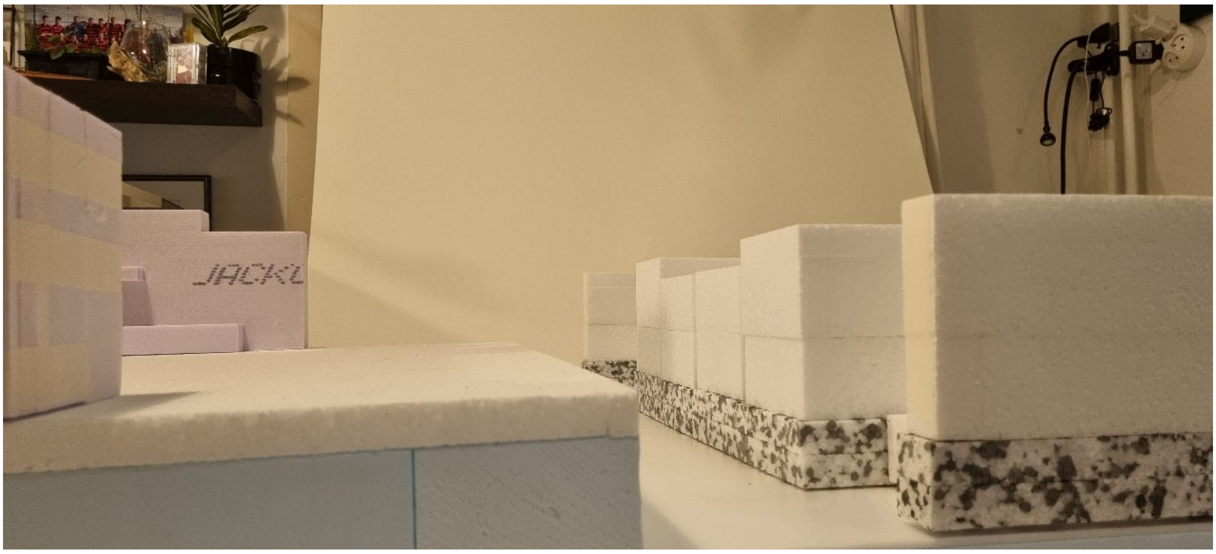
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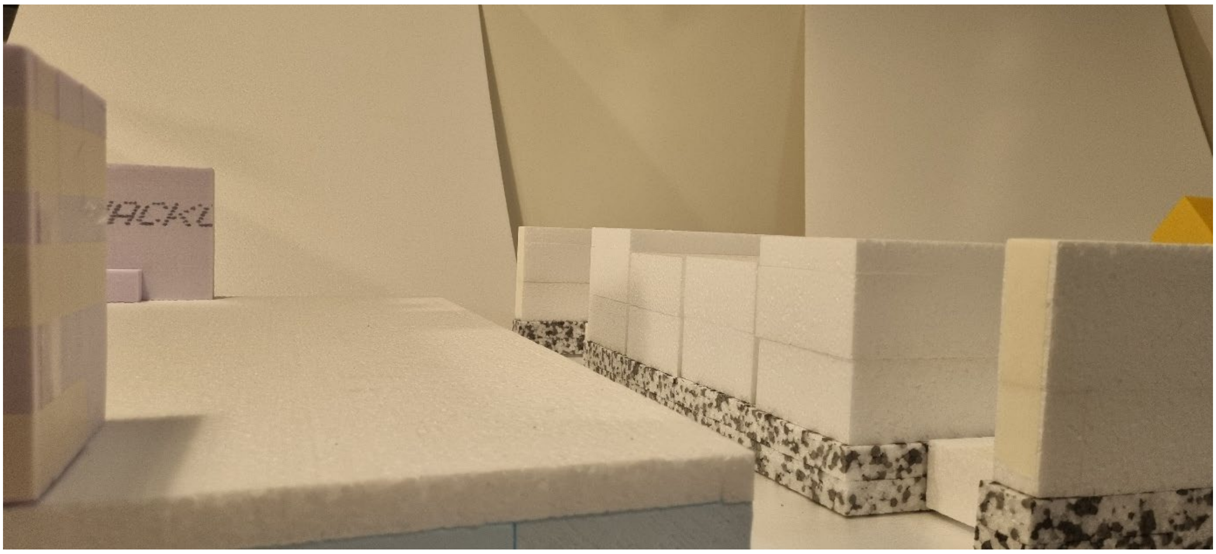

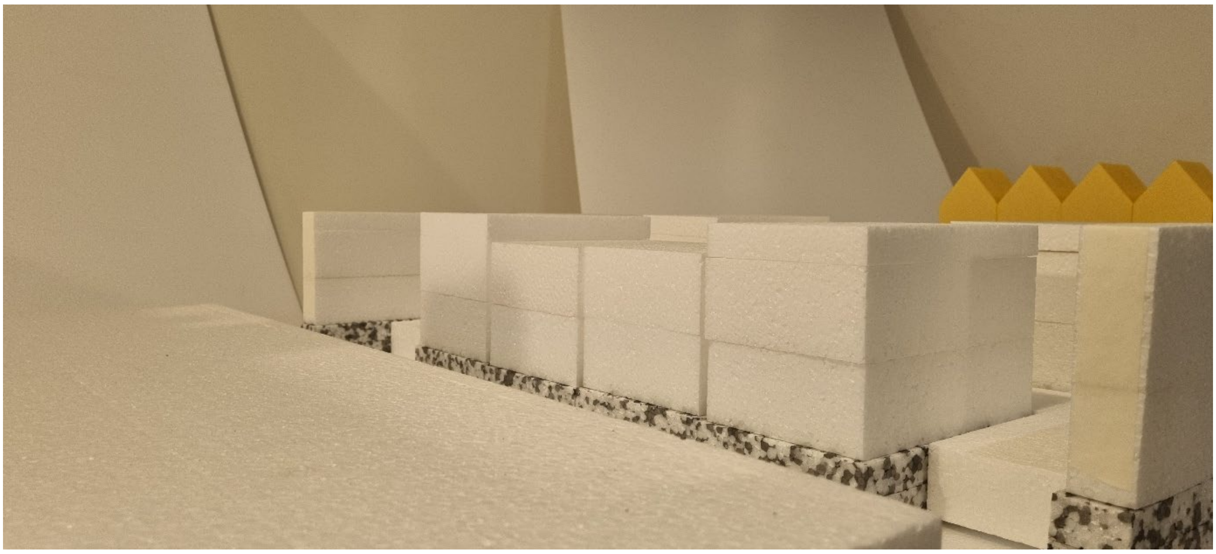


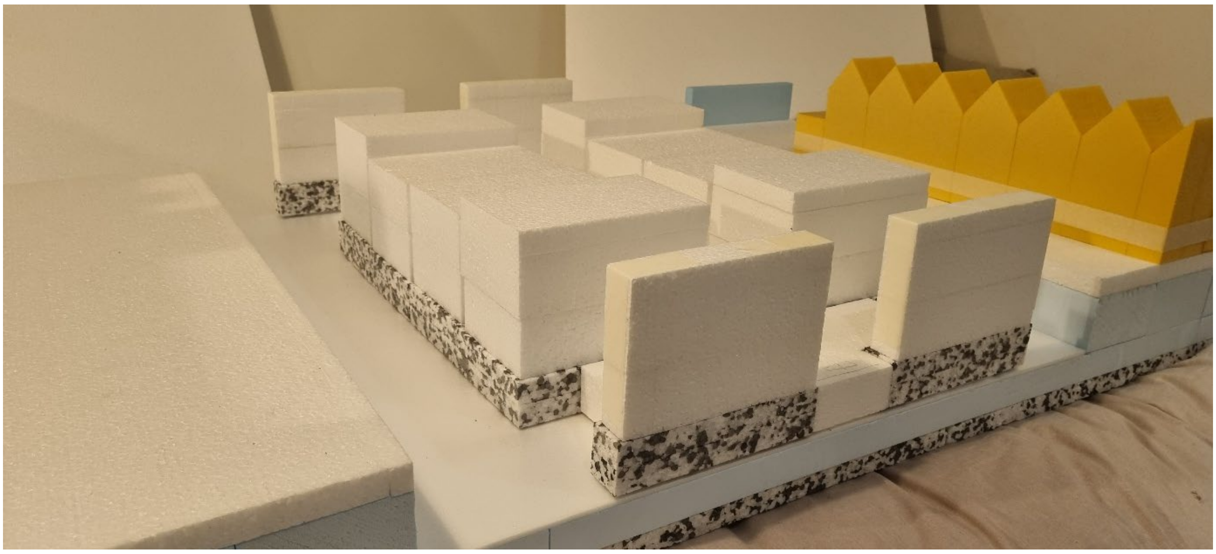


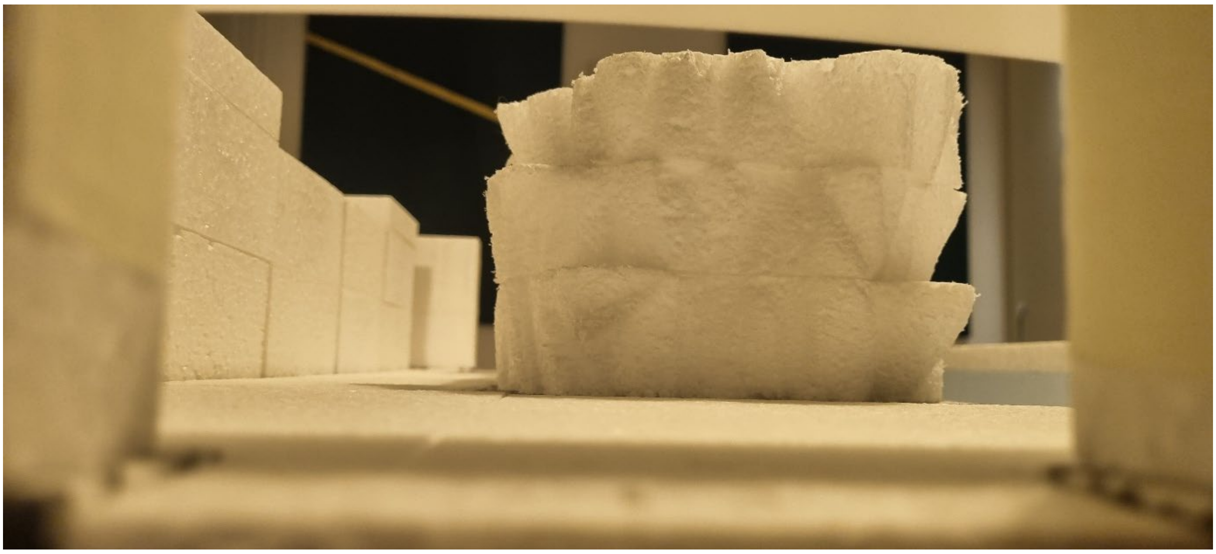

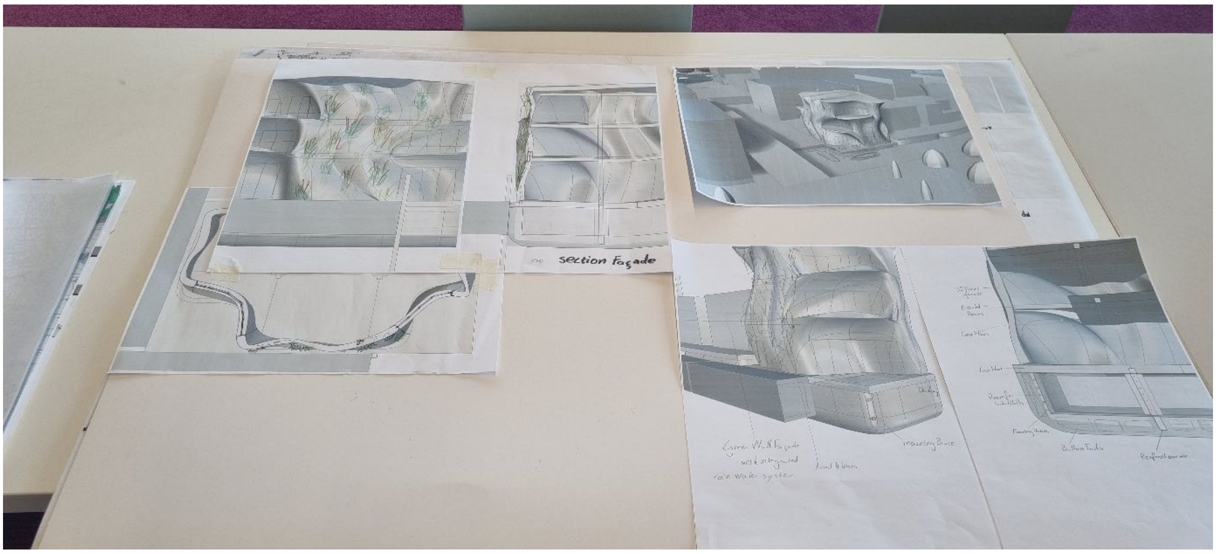
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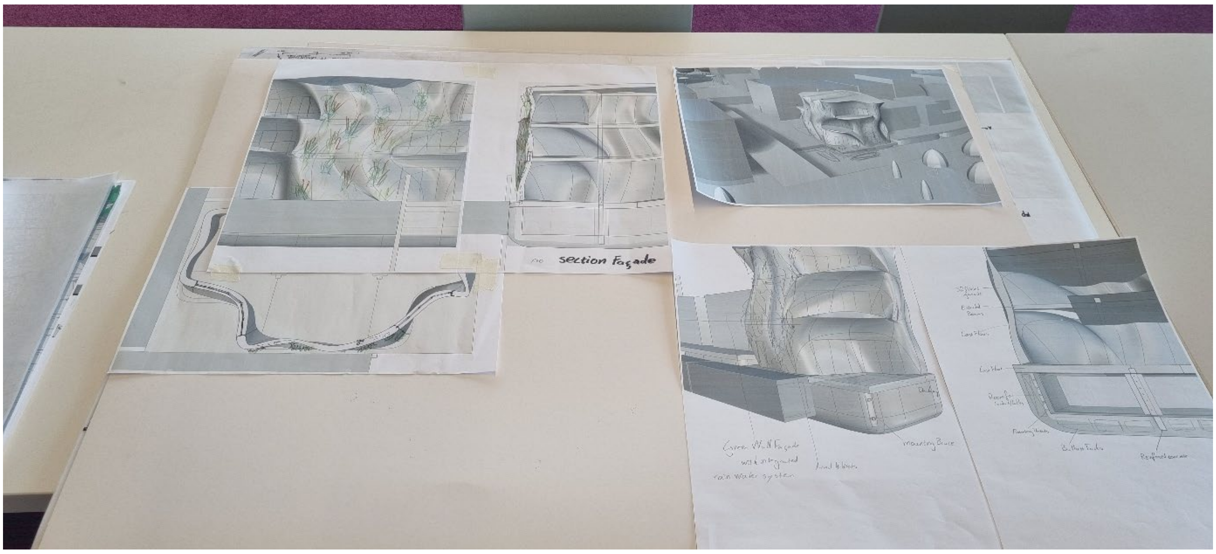
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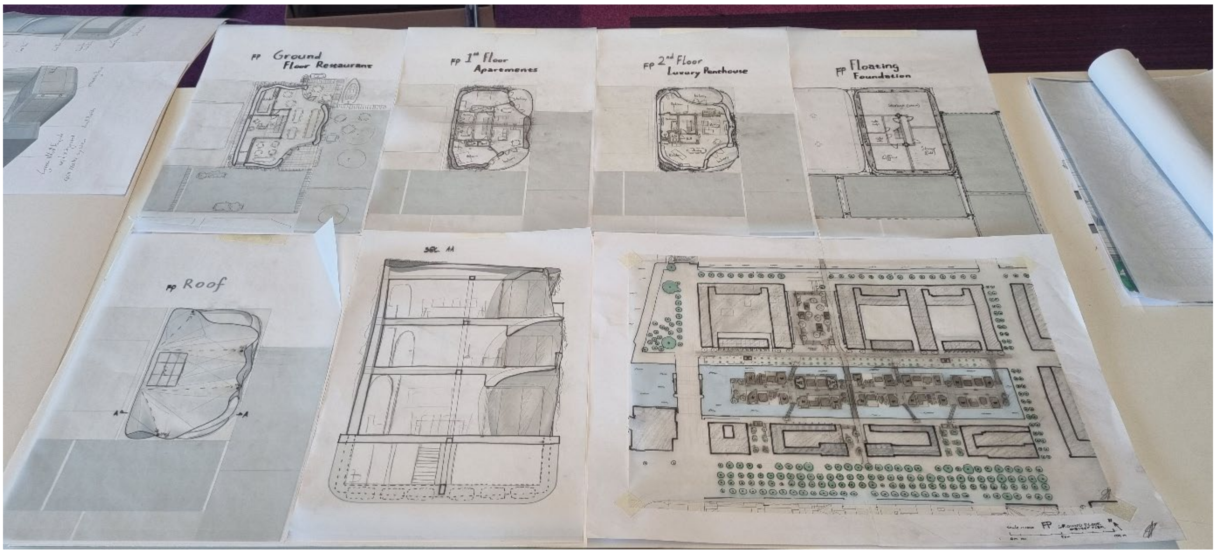
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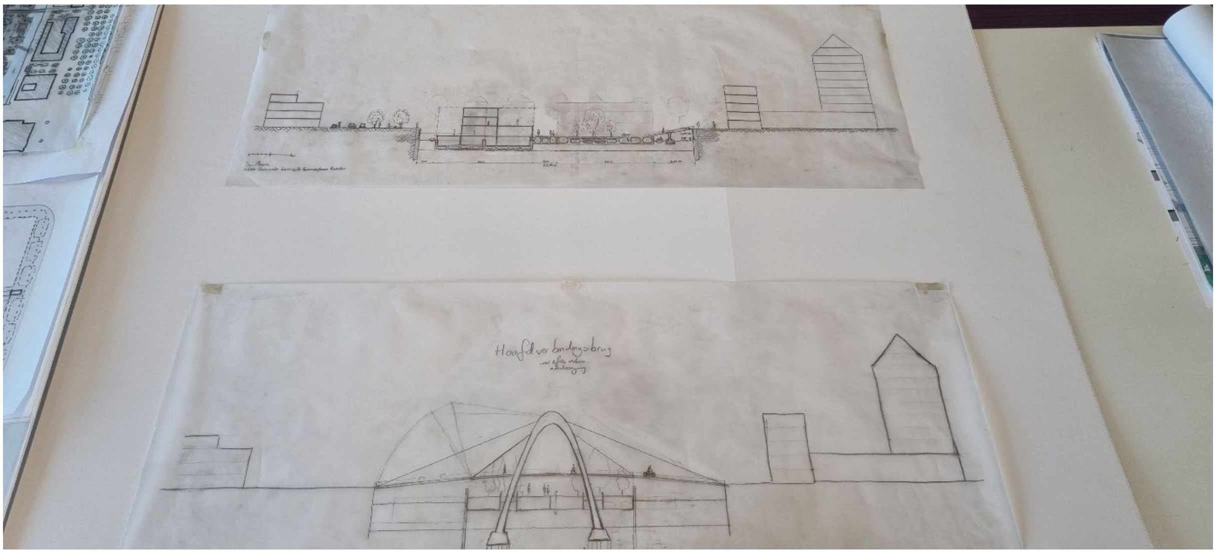
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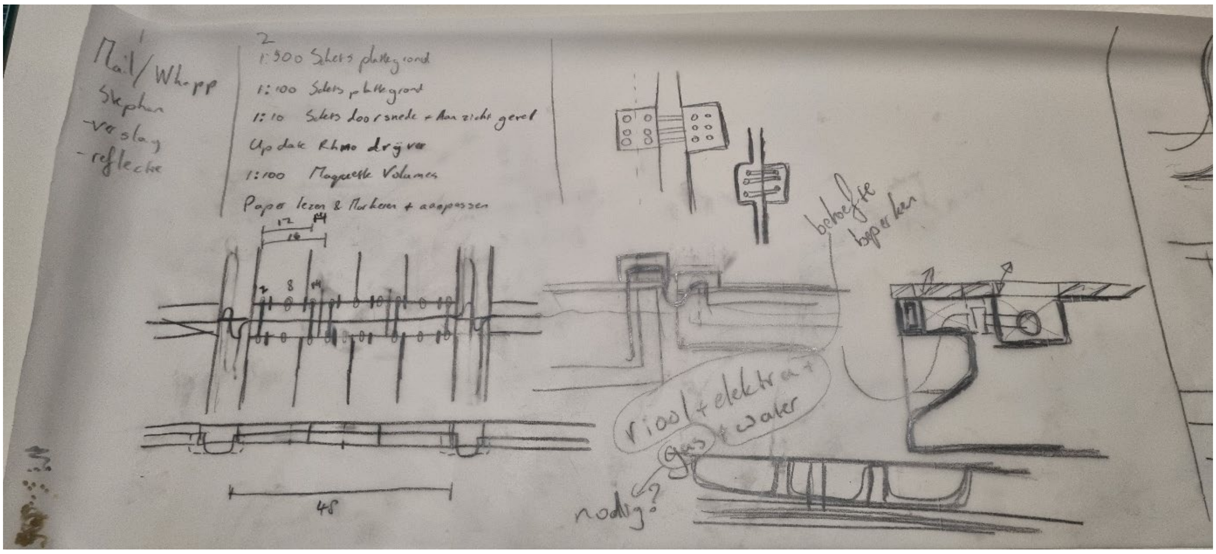
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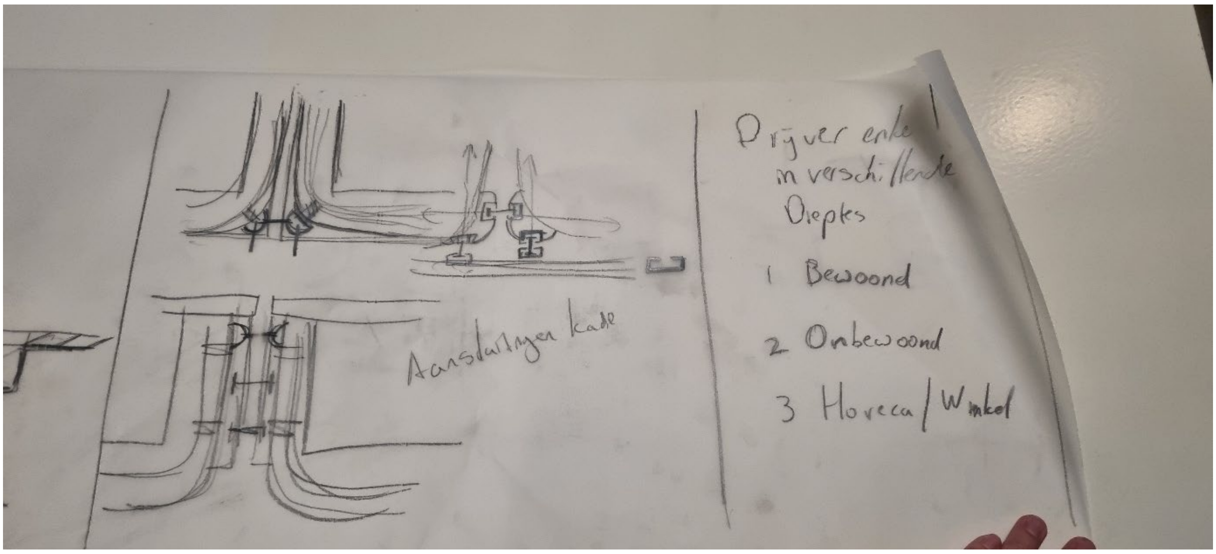
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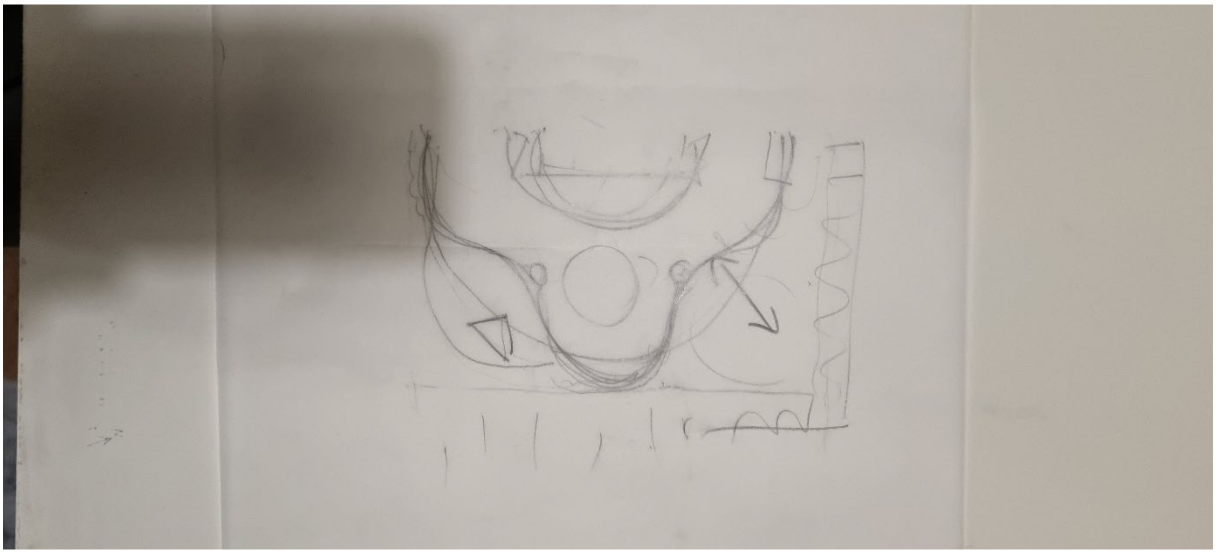

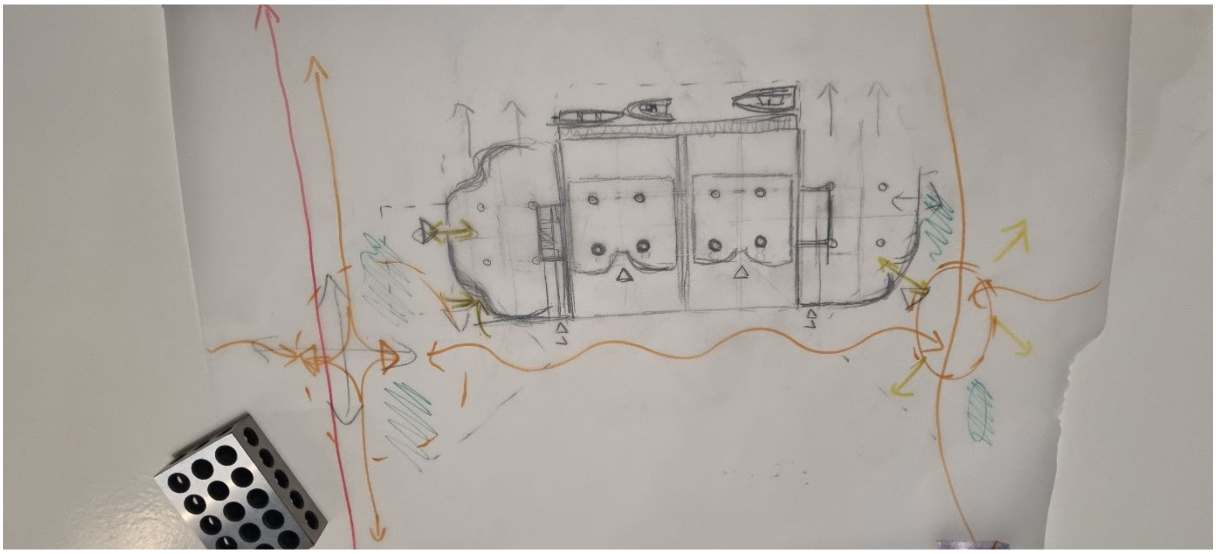

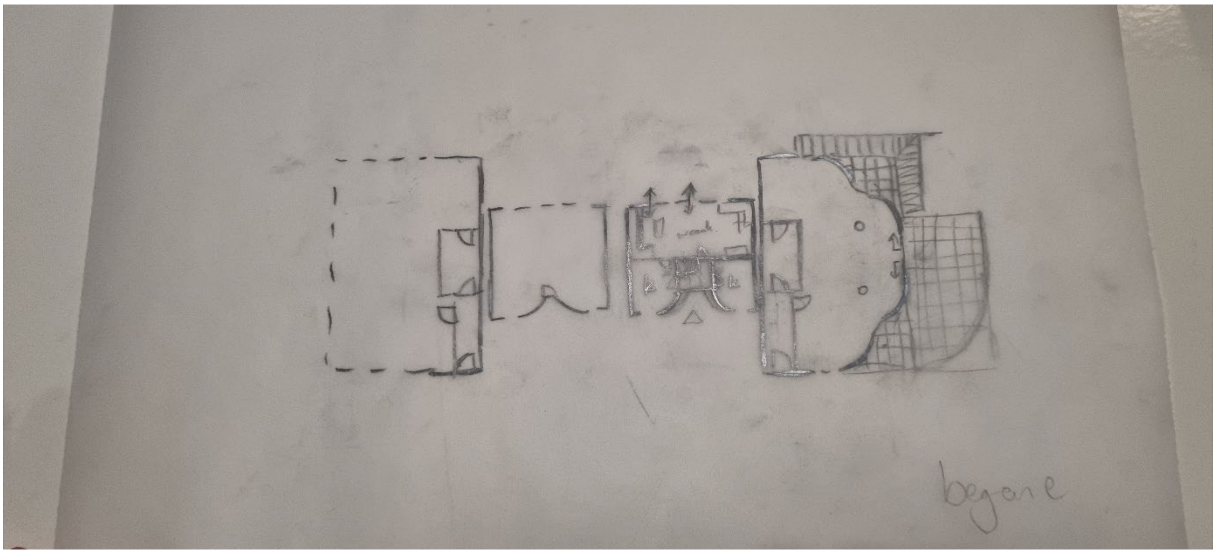
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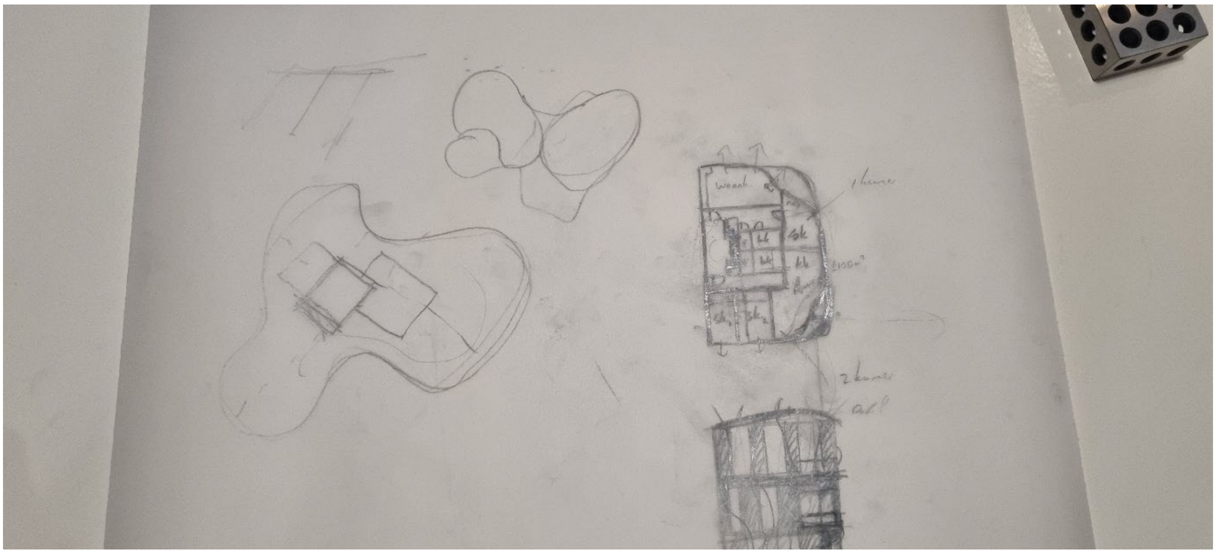

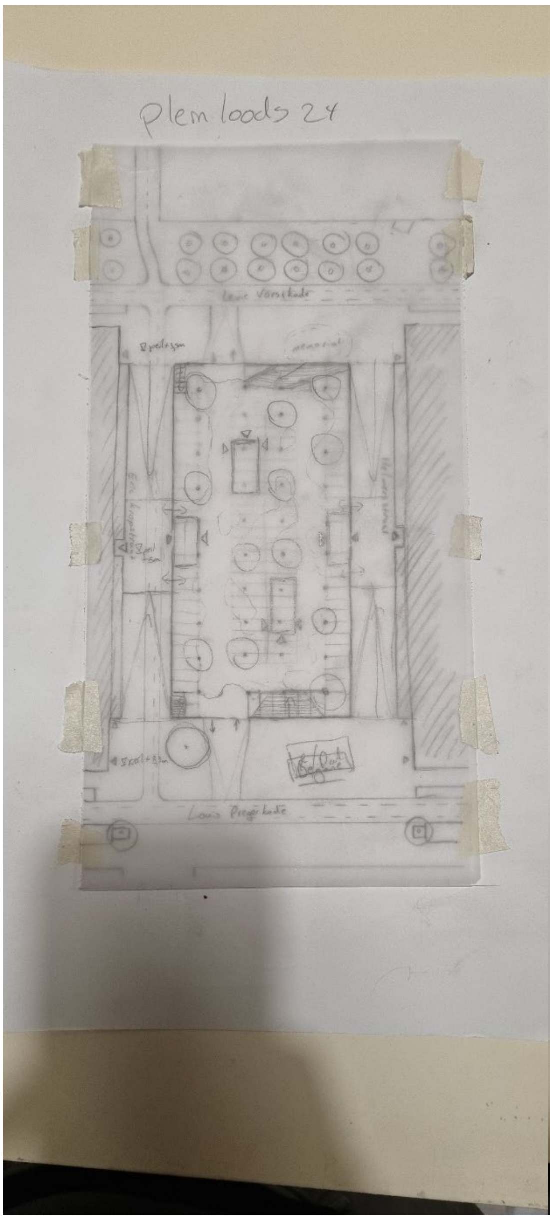
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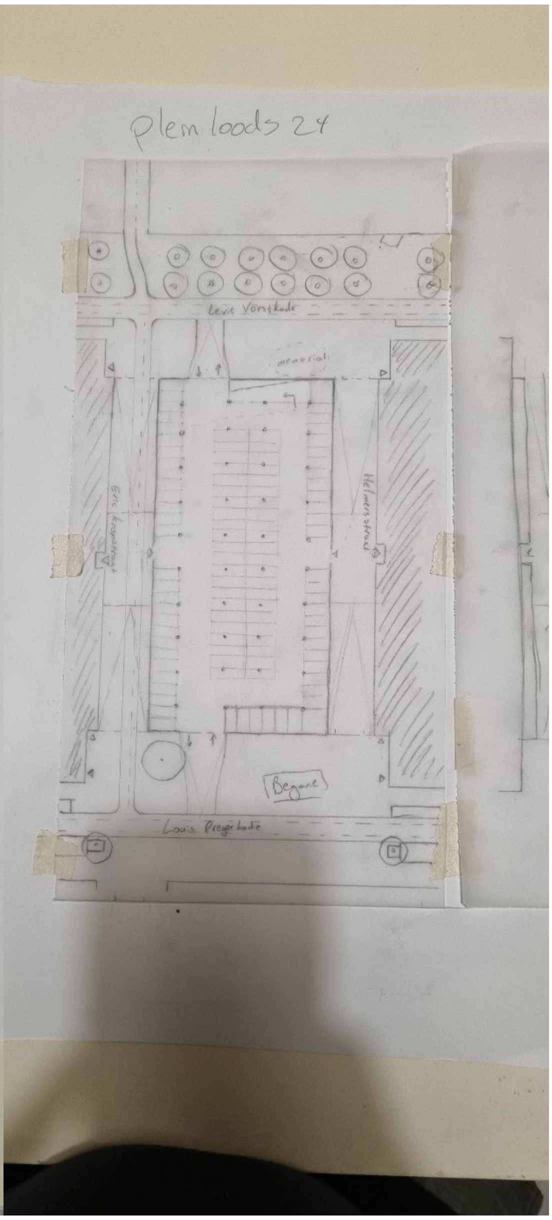
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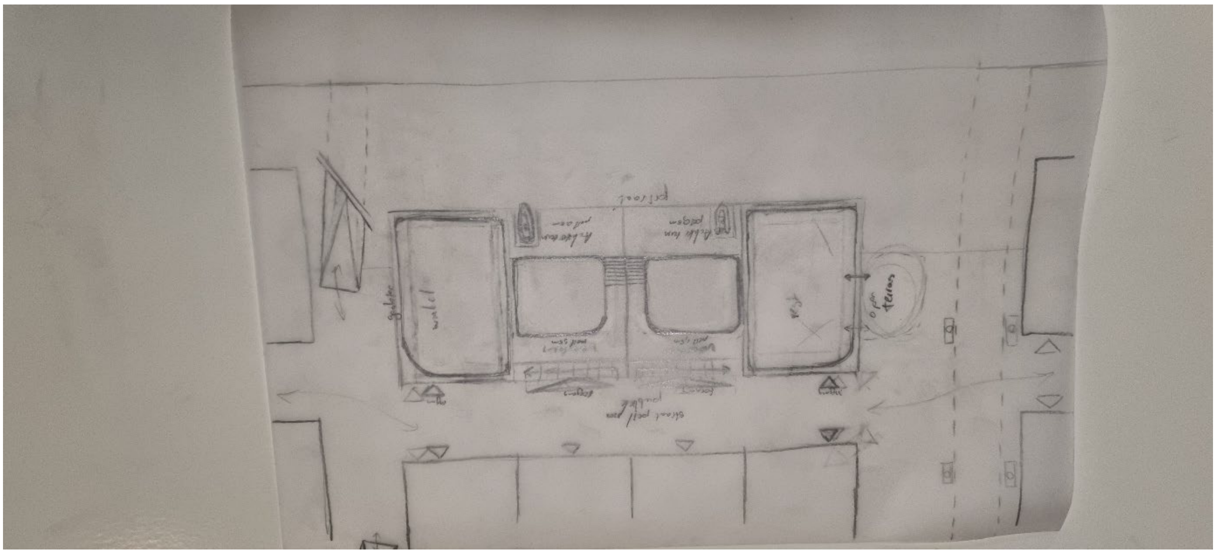

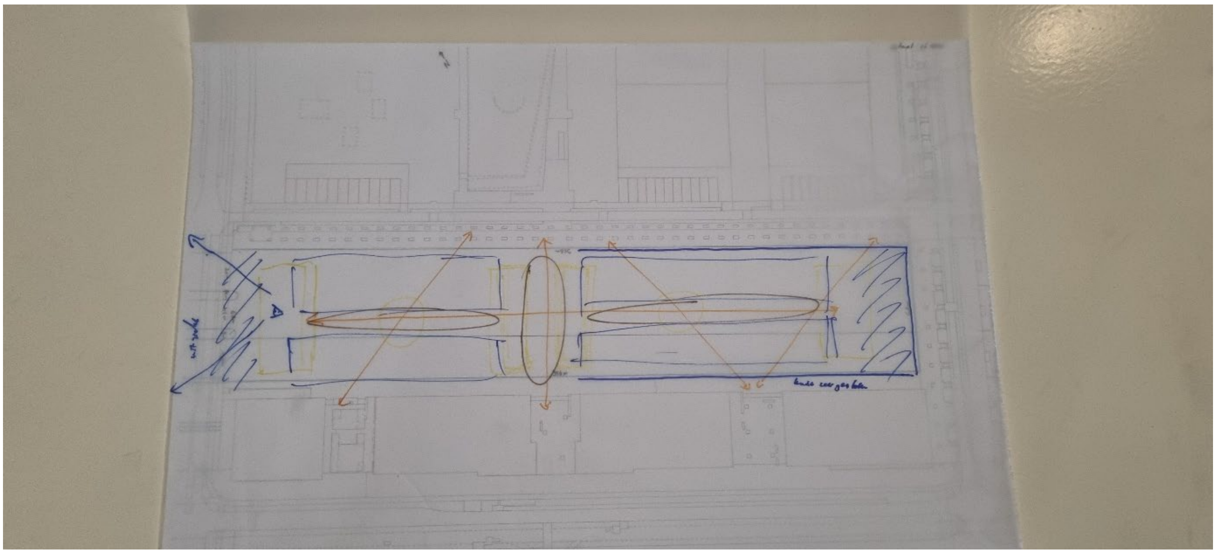

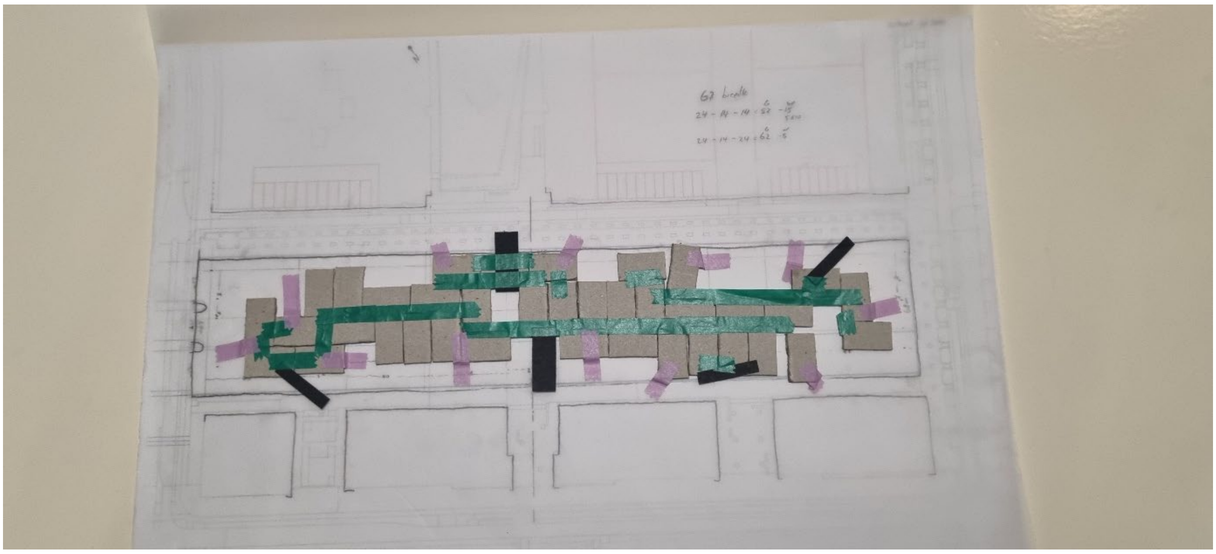

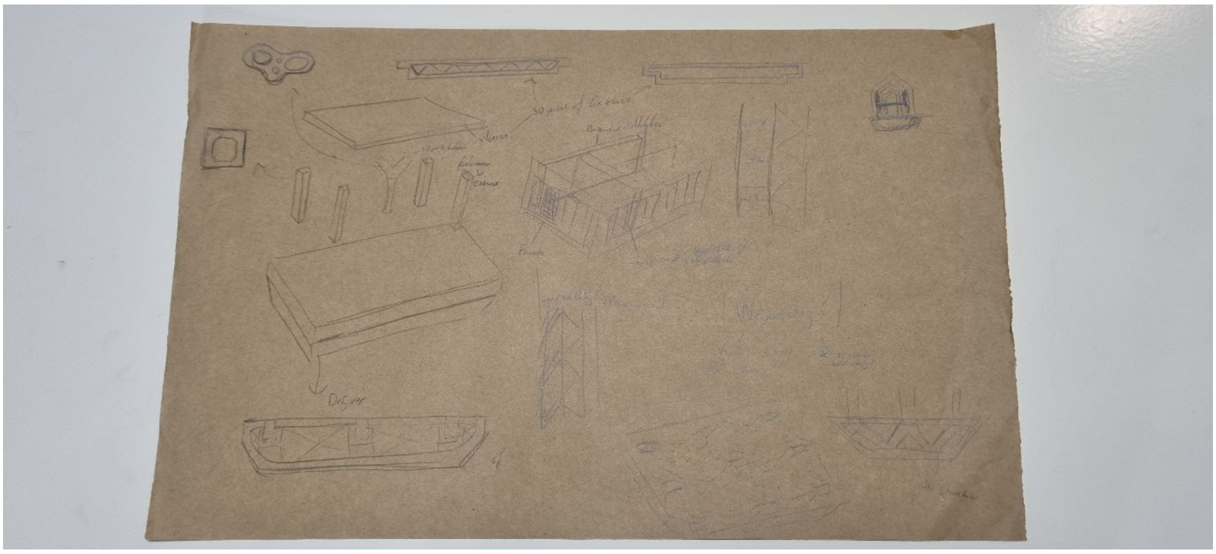

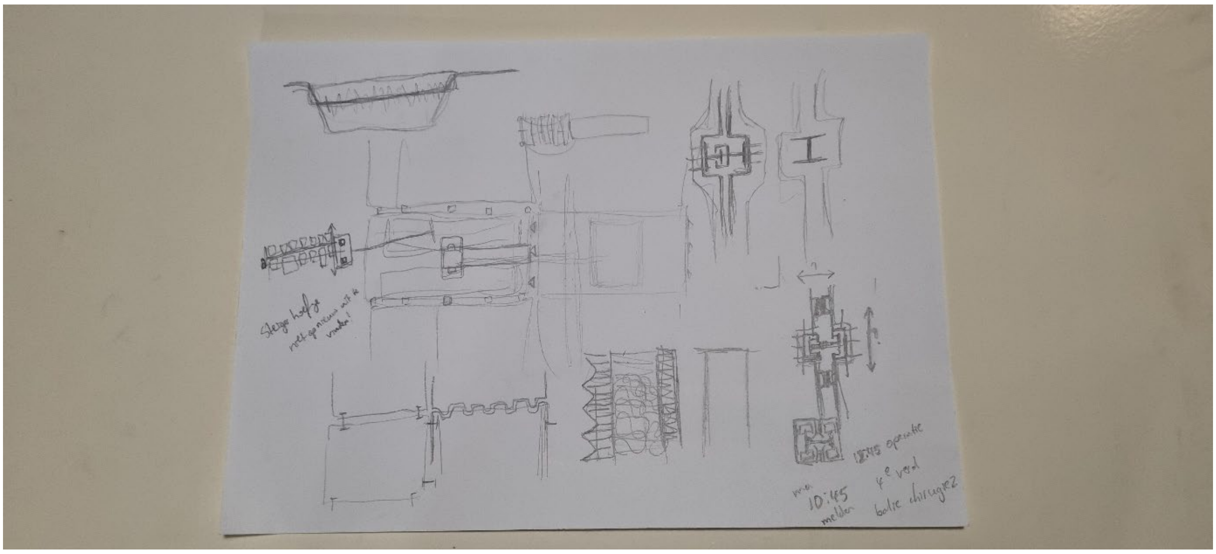
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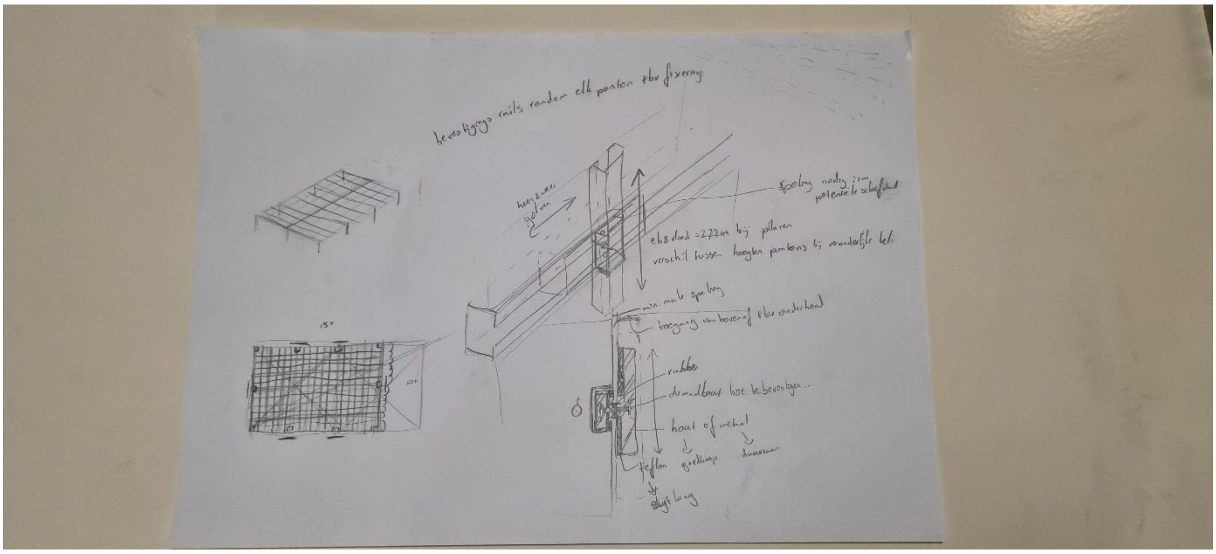
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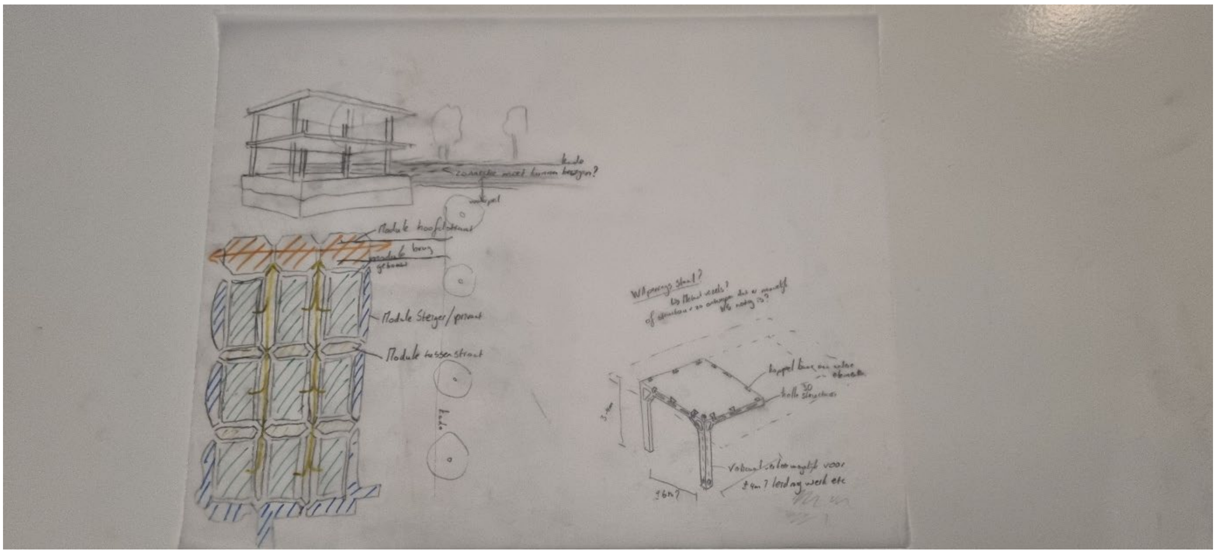
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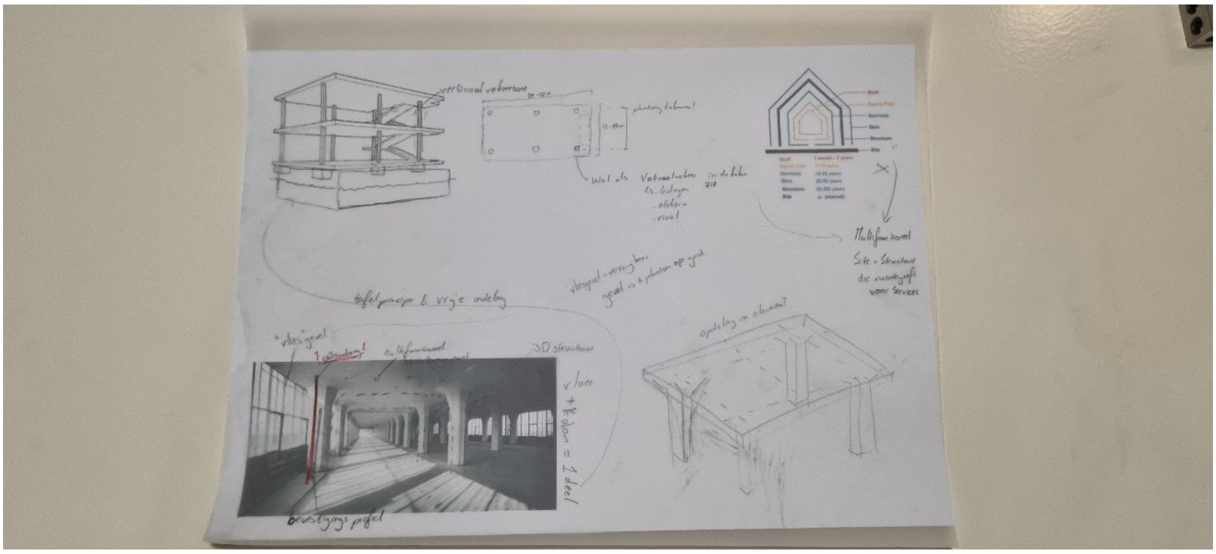
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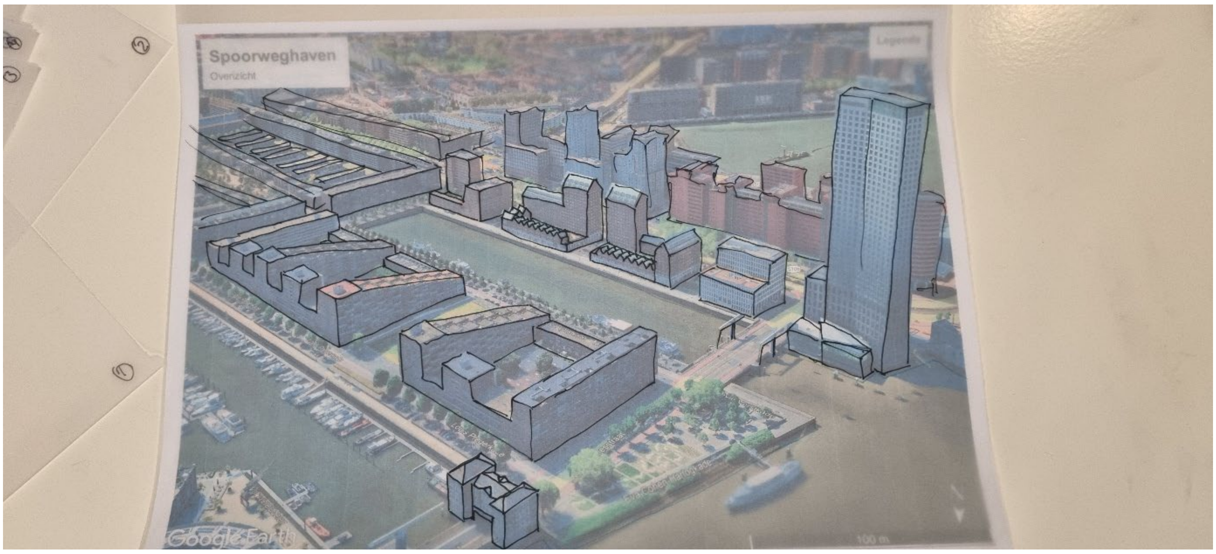
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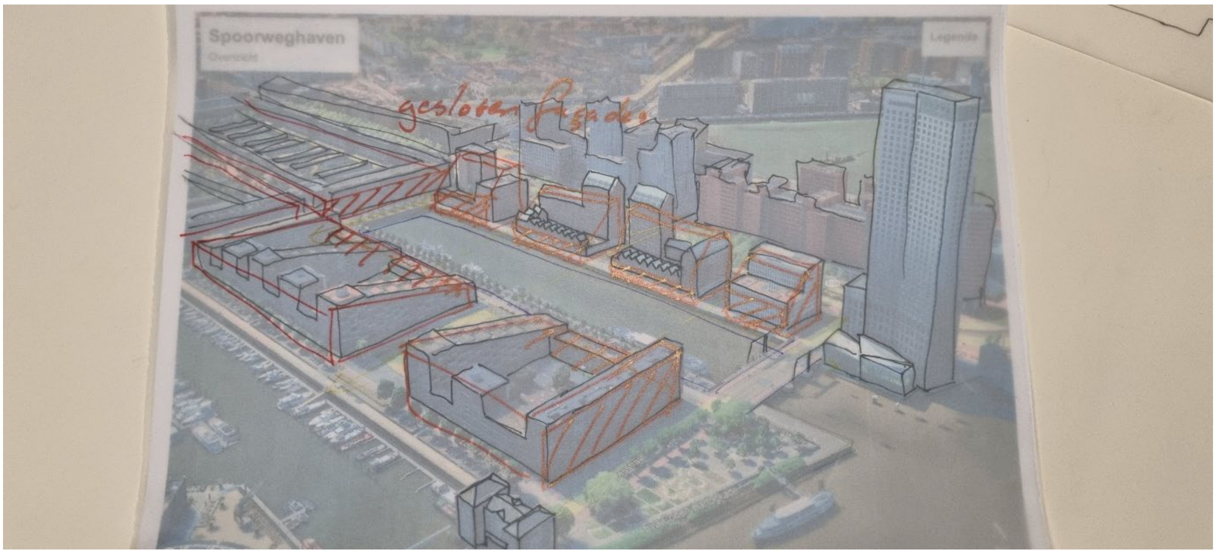
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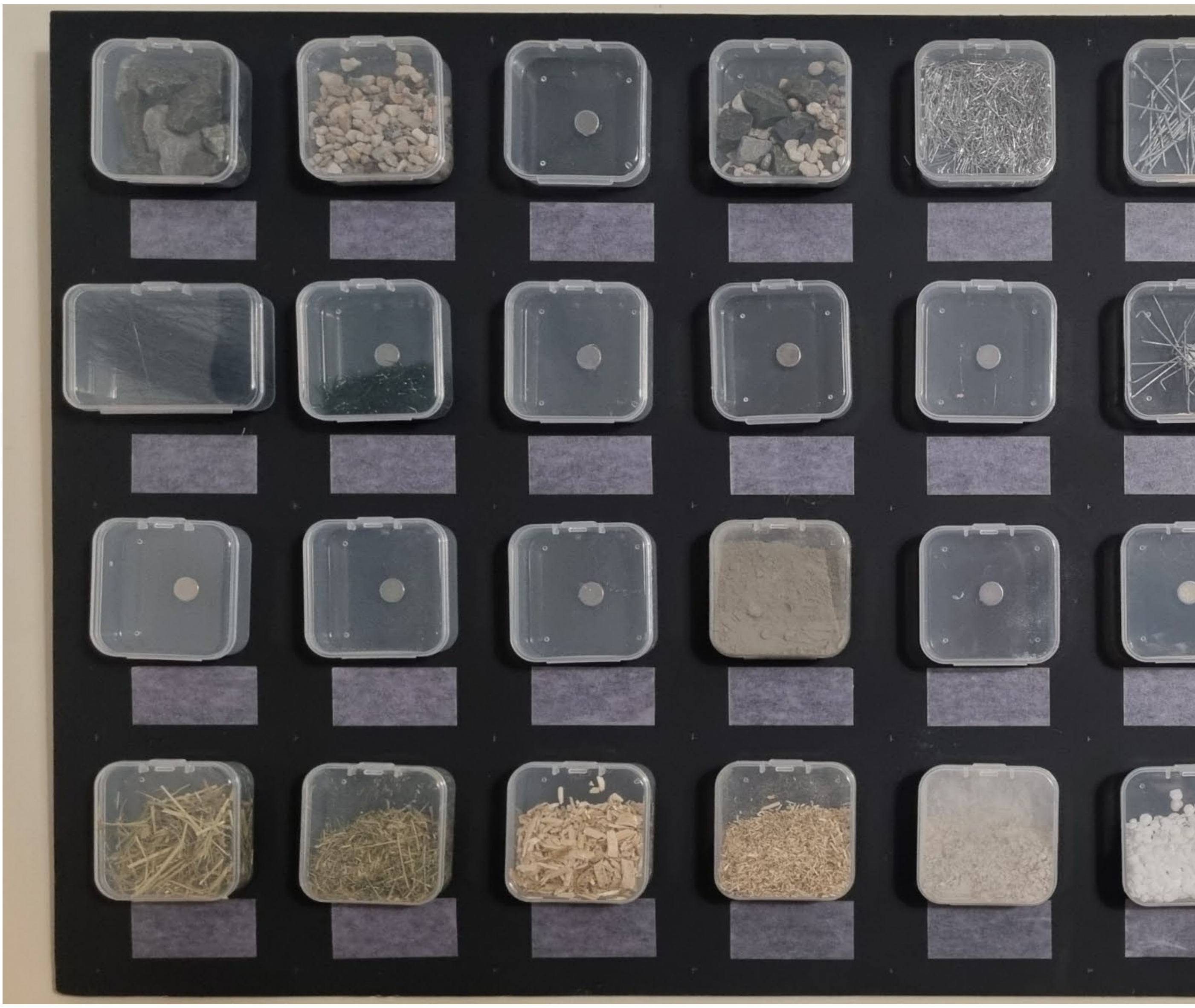

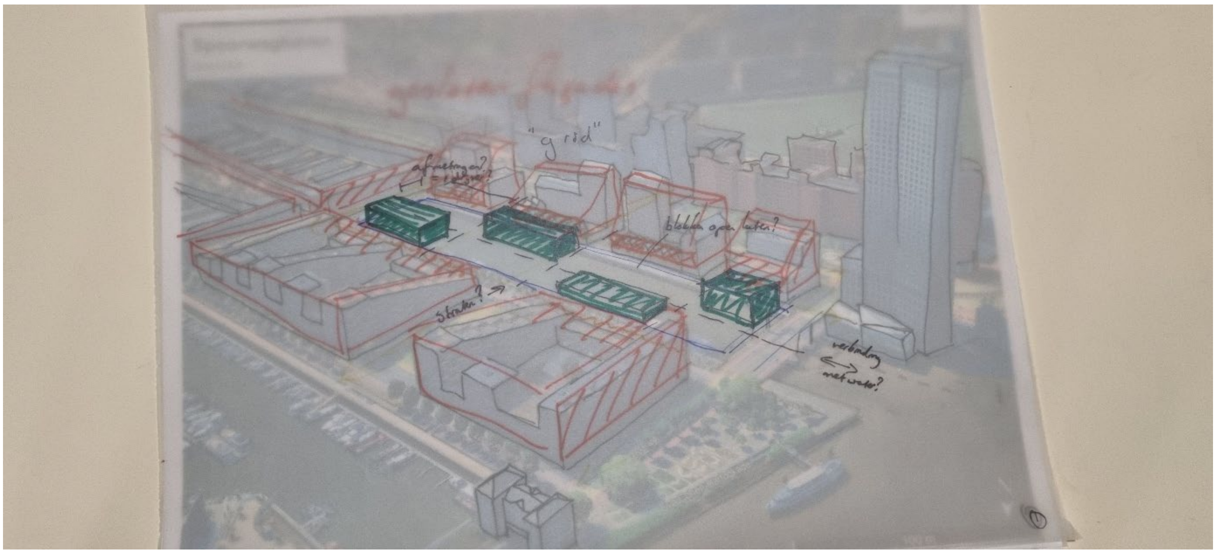

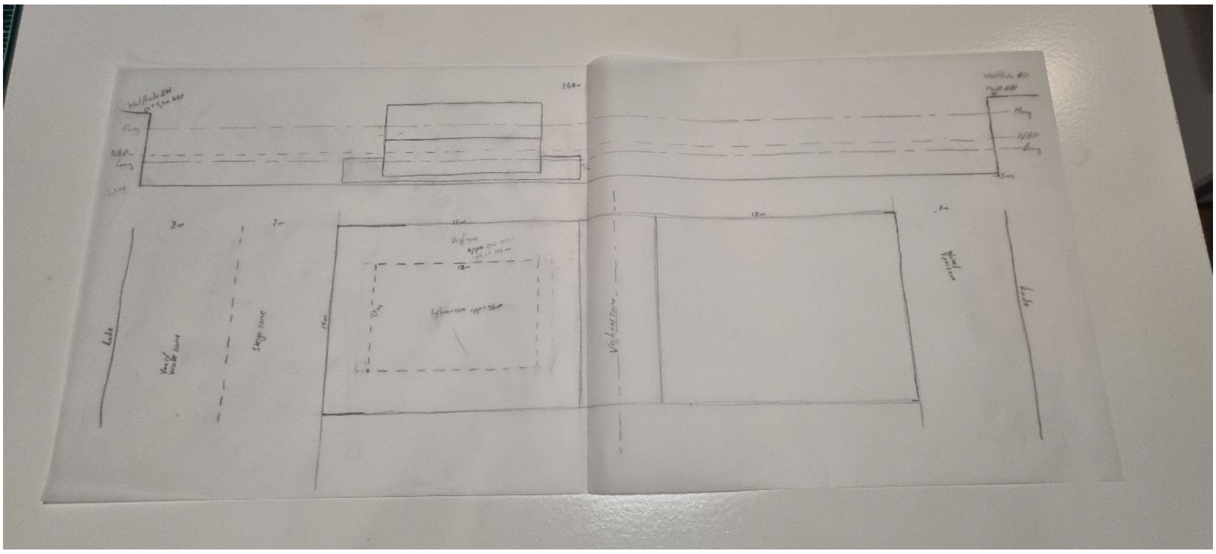

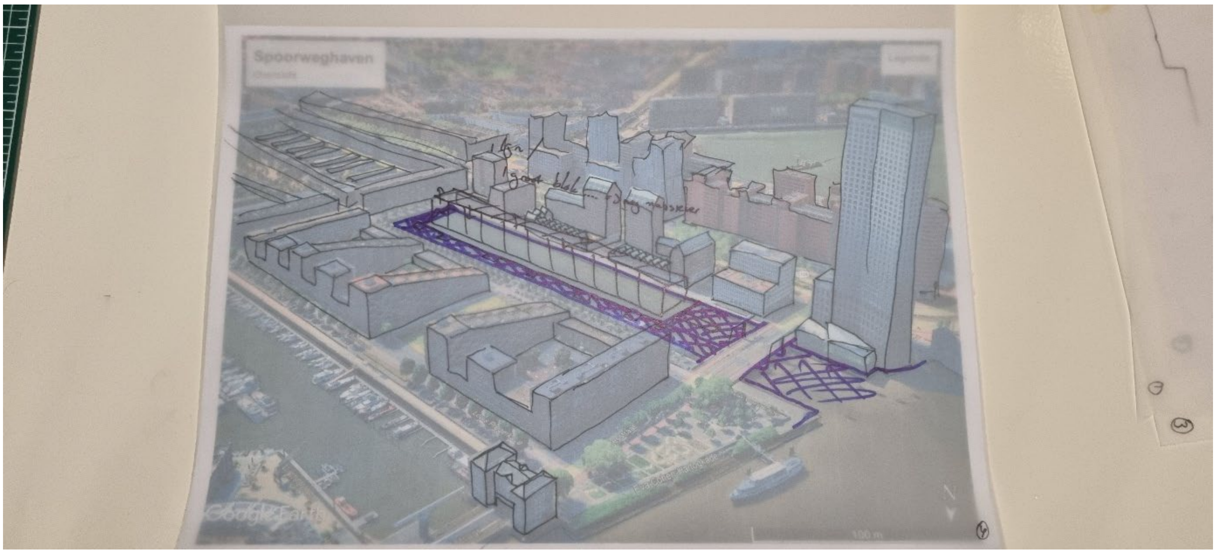
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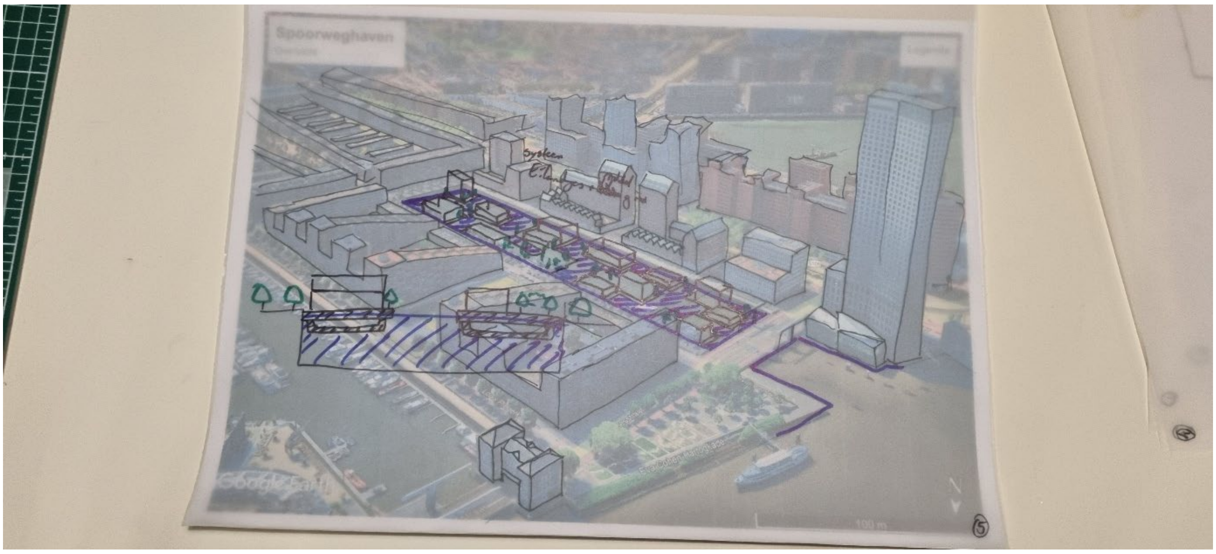
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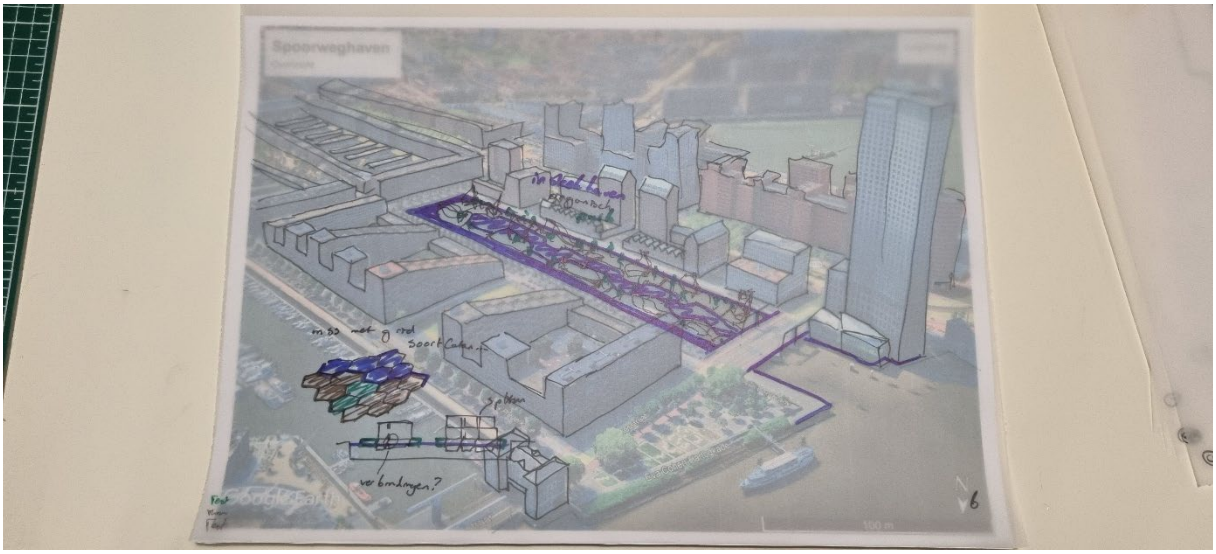
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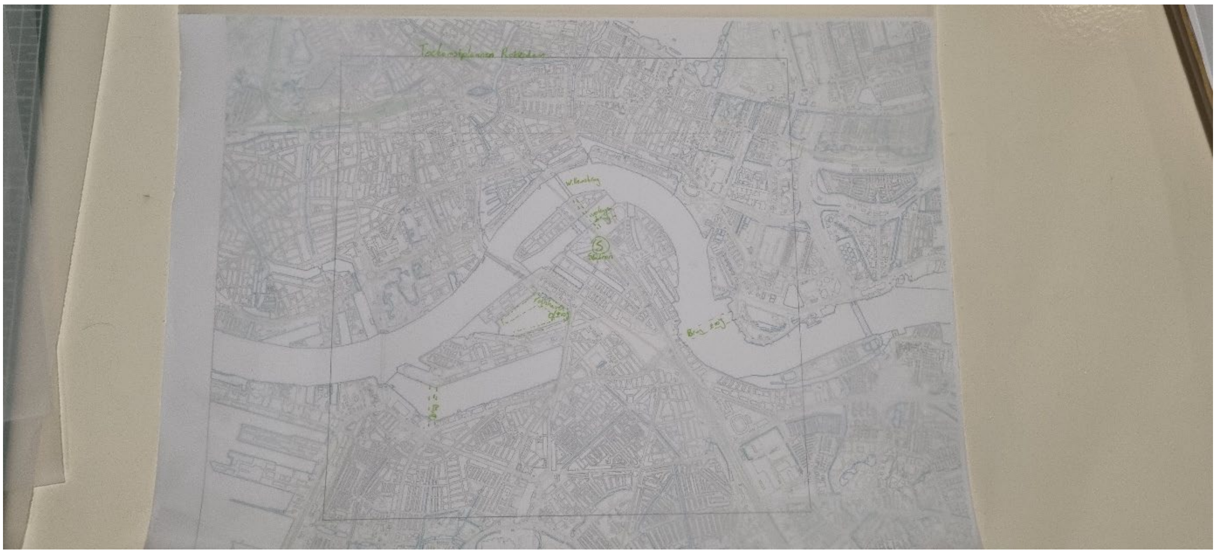


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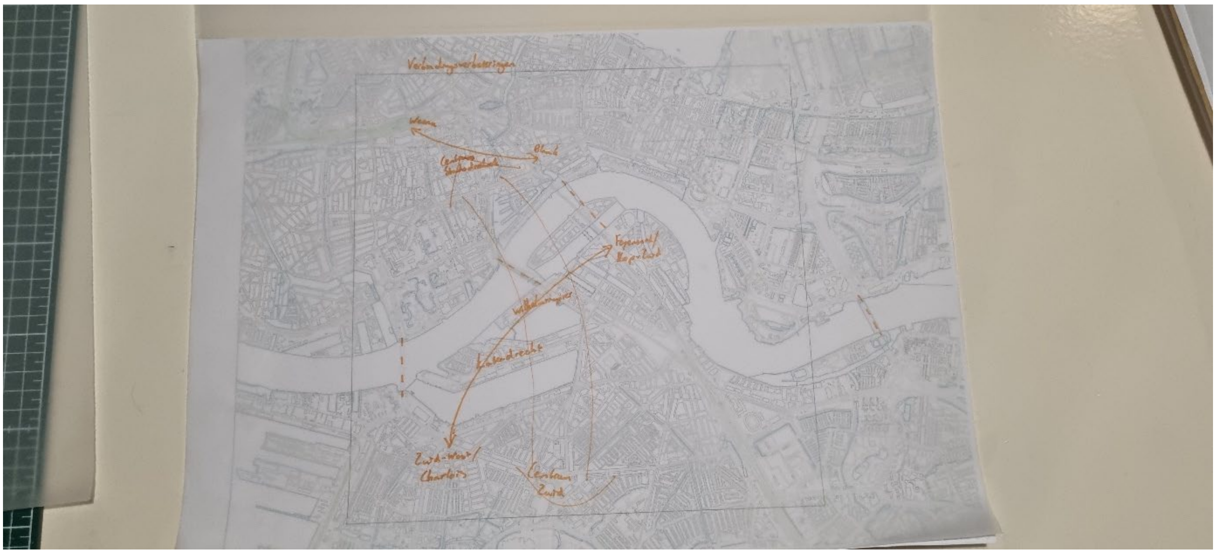
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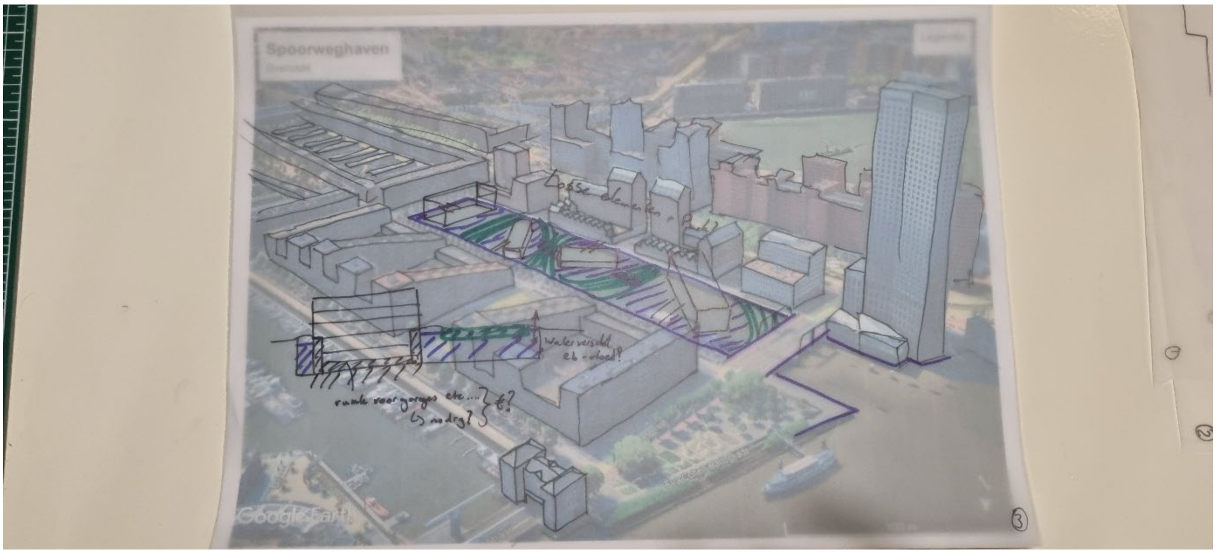
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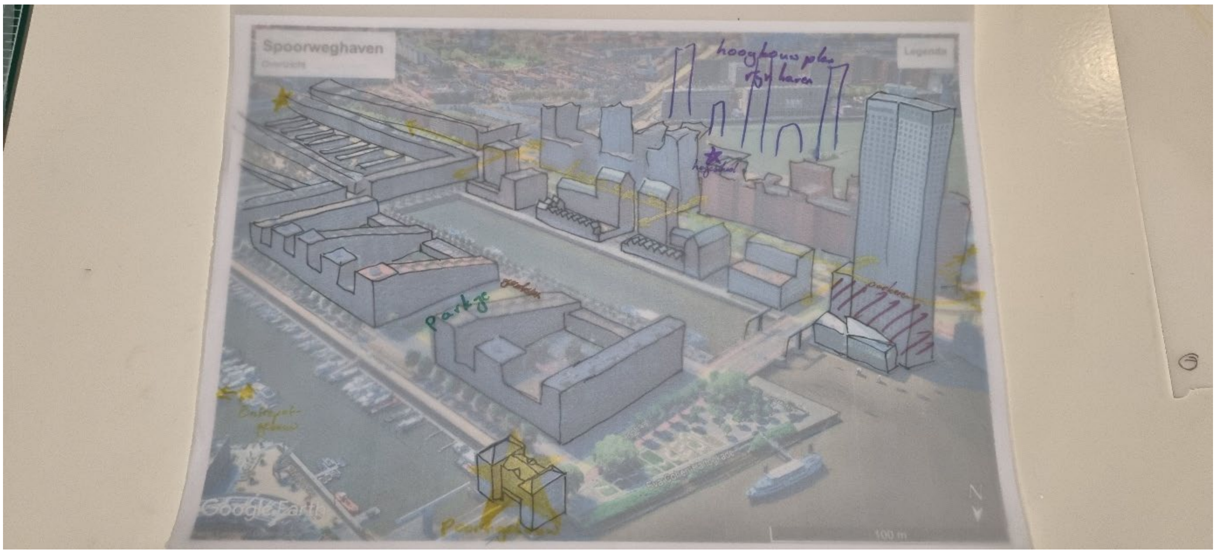
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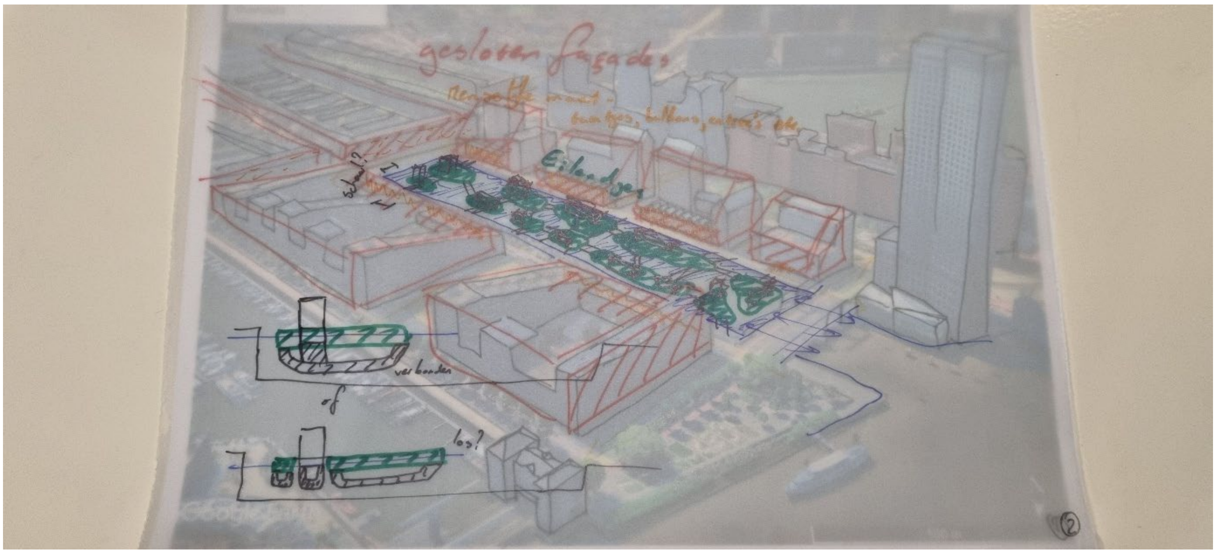
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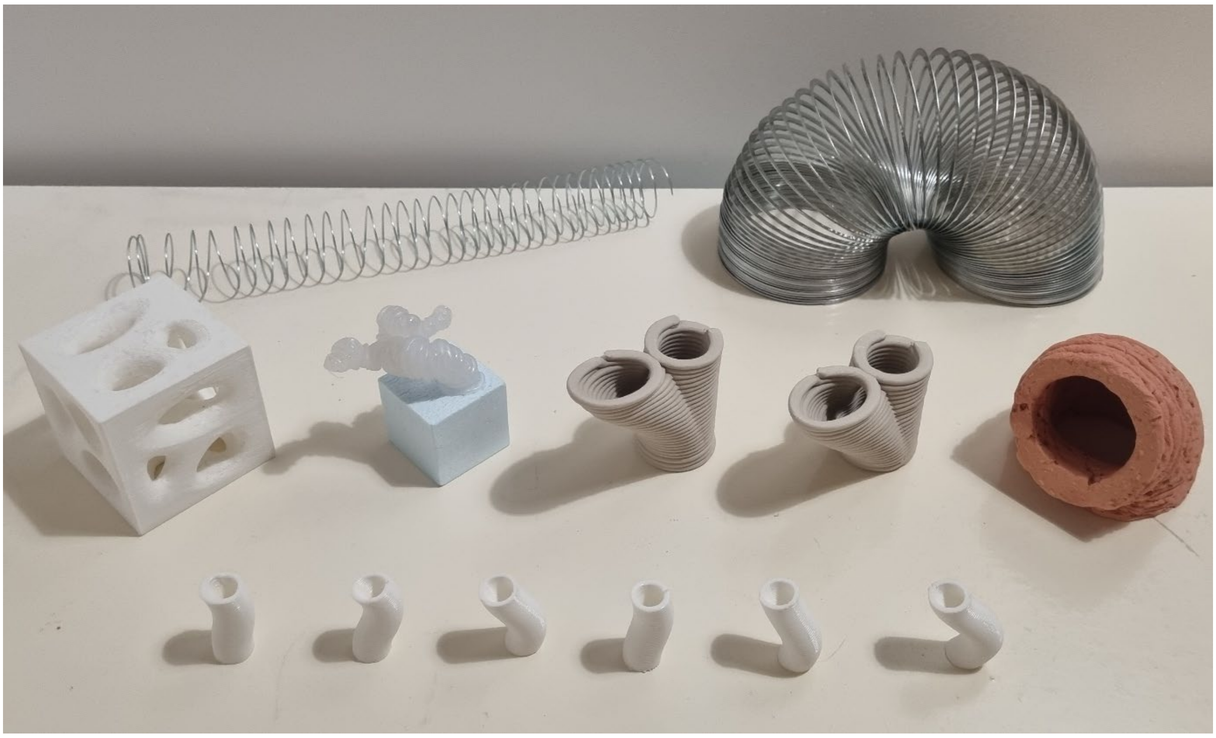

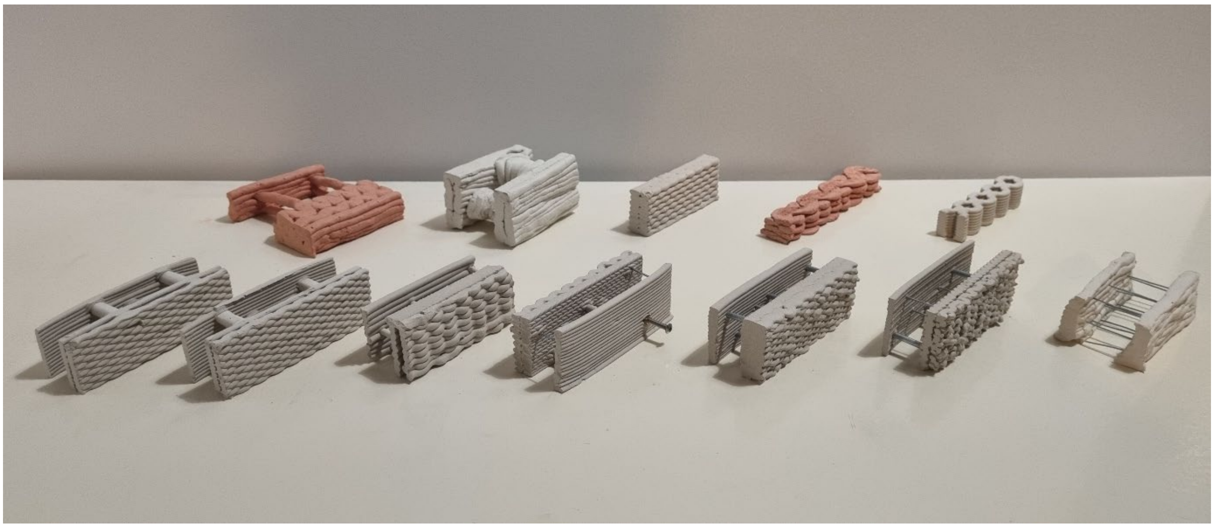

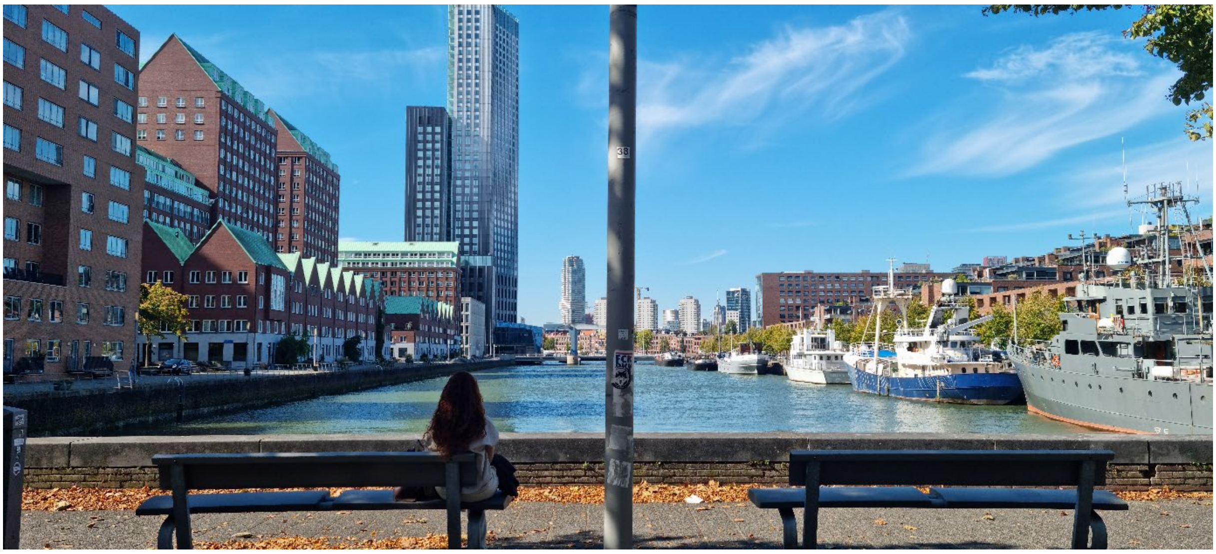

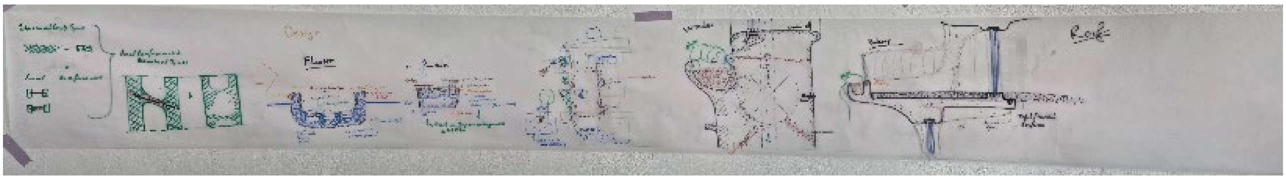

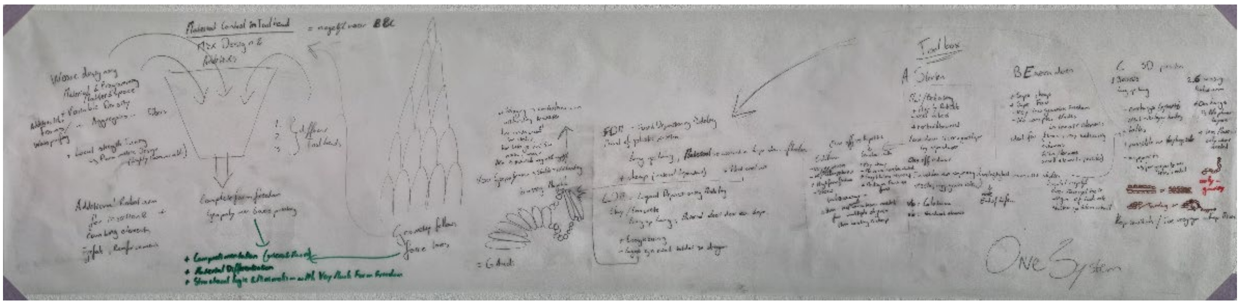
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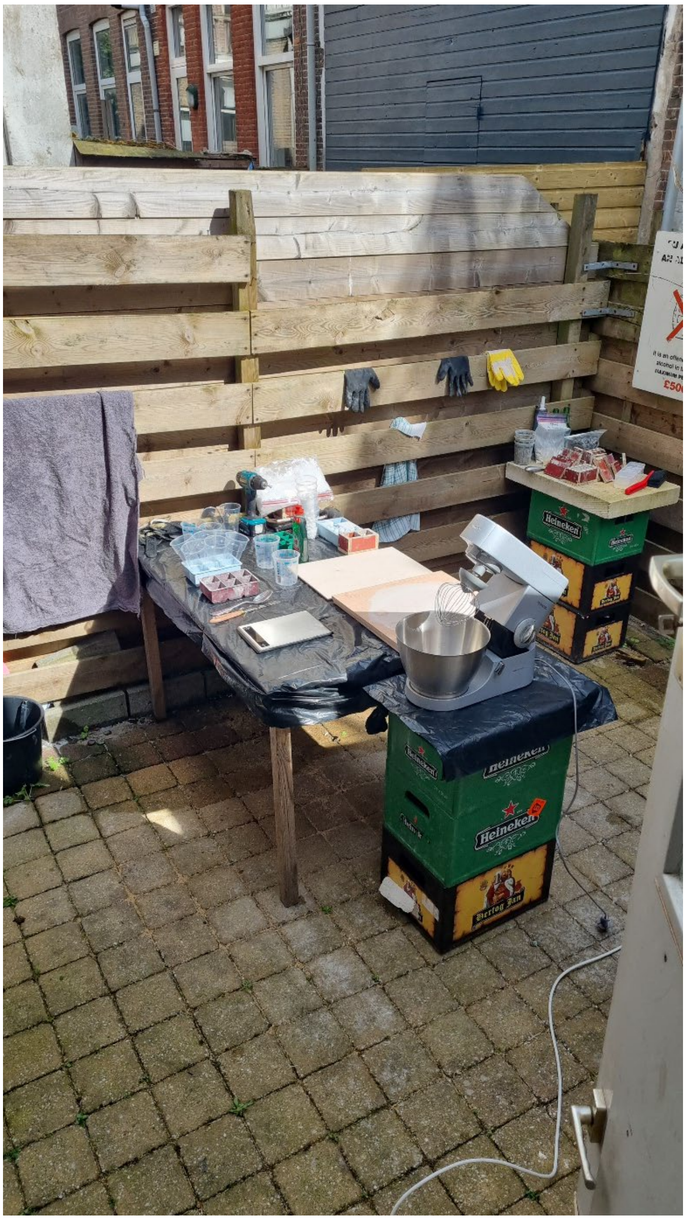
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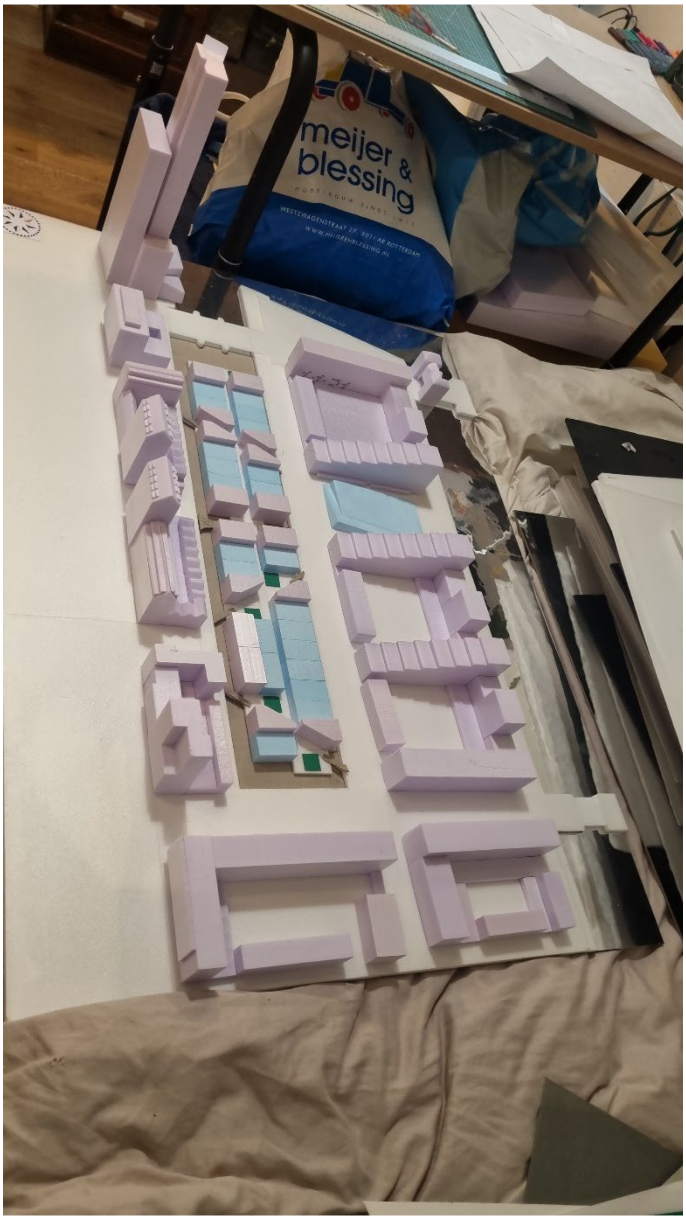
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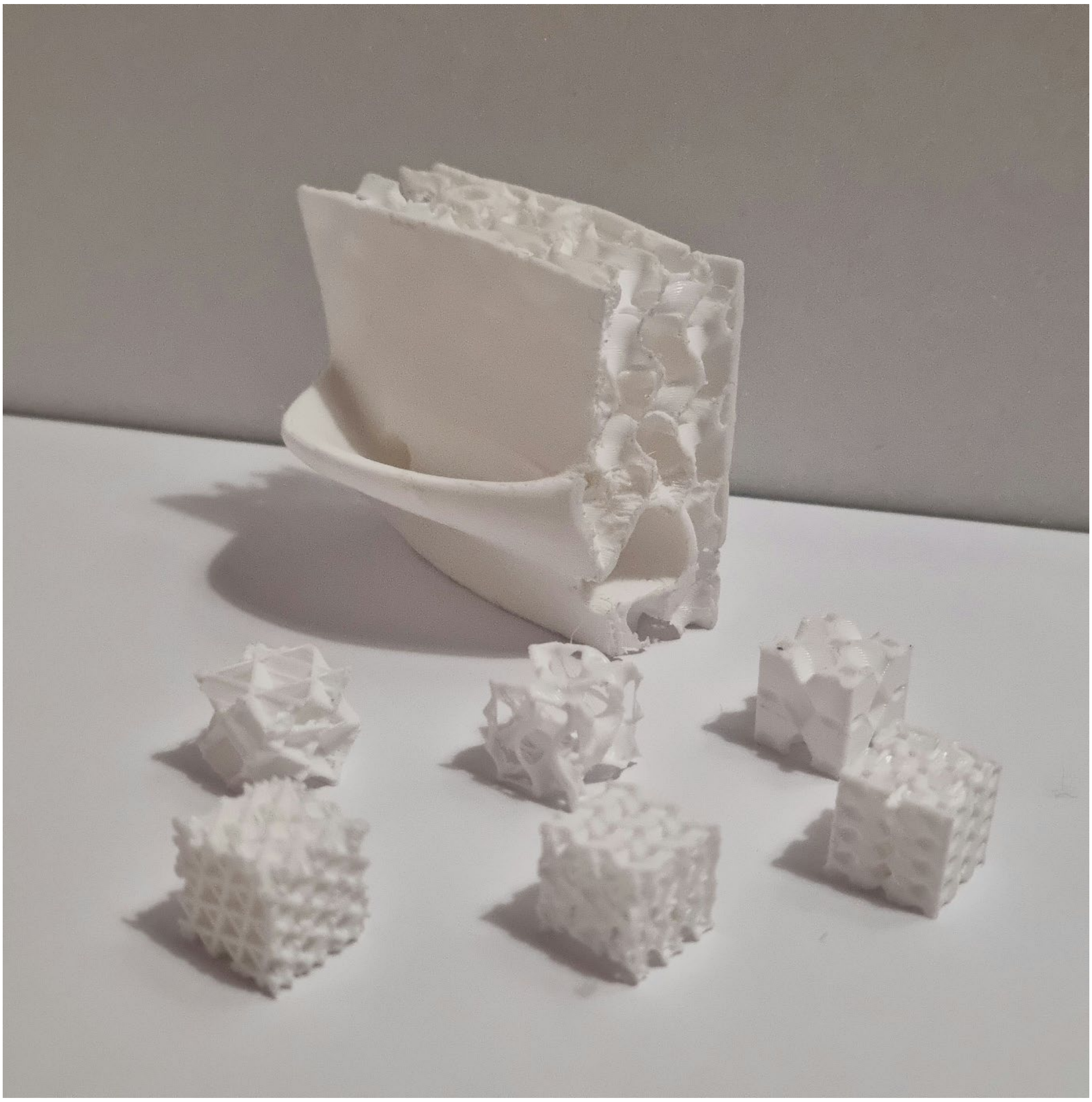


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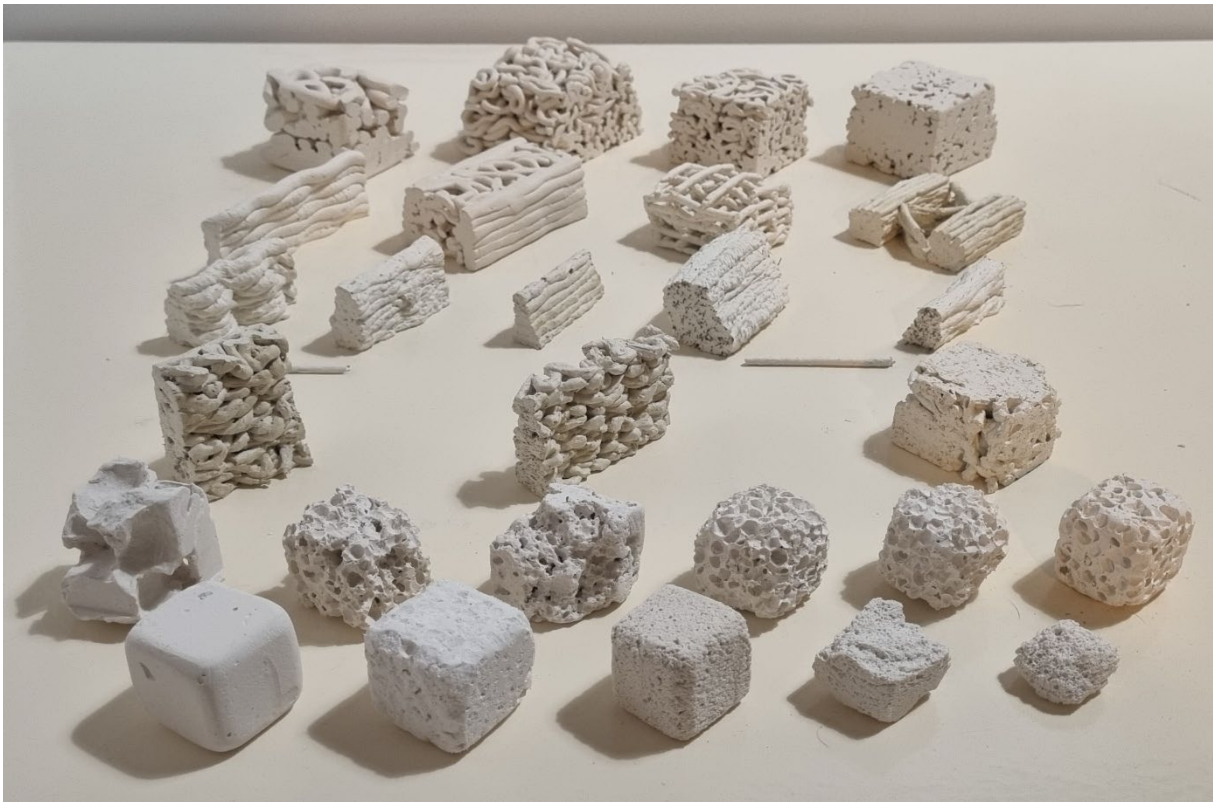

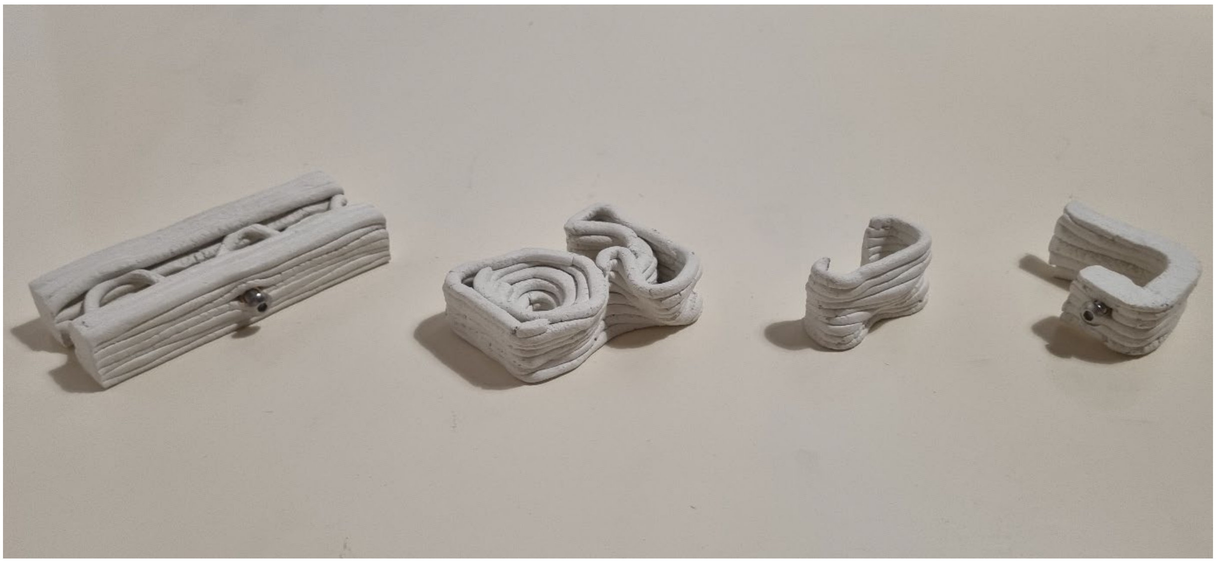

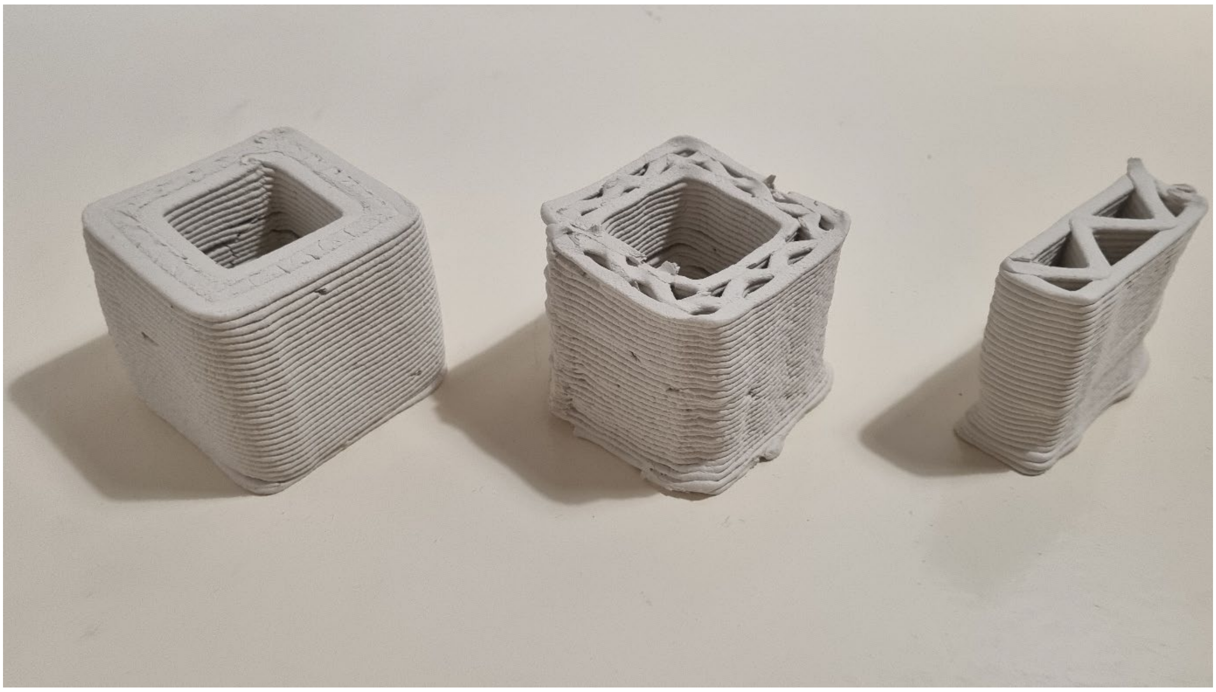

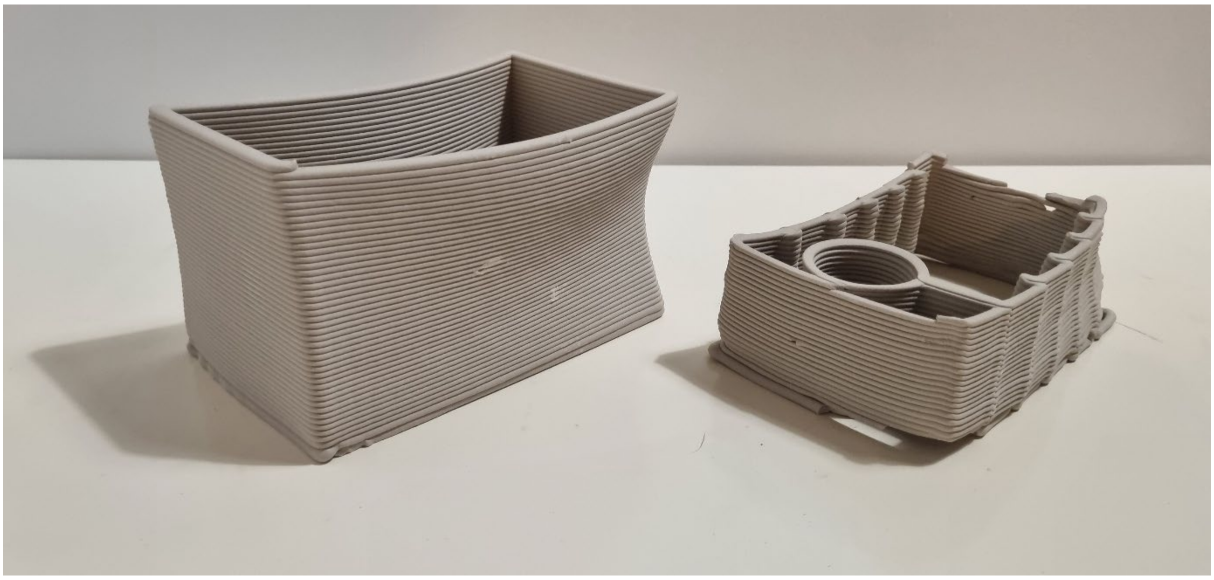

Reflection:

Waterwijk Spoorweghaven / Spoorweghaven Waterfront District

This graduation project is developed within the Architectural Engineering (AE) graduation studio and positions itself within the studio 3 pillar framework of Flow, Stock and Make. . Grounded in the in-depth material research developed through my paper "Dutch Waste to Circular Structure: An Overview of Geopolymer Concrete in the Dutch Context," the project investigates how circular material innovation can inform a systemic urban proposal.

The project translates Stock through the development of a circular material logic based on geopolymer concretes combined with use of building demolition waste materials. Flow is looked at through the investigation of how such material systems can operate within Dutch conditions and locally available resources. Make is translated within the exploration of prefabrication conditions and a toolbox of pooring, extrusion-based and additive manufacturing concrete element production methods. These 3 pillars were as such gradually translated into concrete design criteria, spatial decisions and structural aspects within the design and research

The decision to choose the Spoorweghaven in Rotterdam as design location was not decided to develop floating houses as a stylistic gesture but as a critical testing ground. It provided a context demanding enough to confront material behaviour, structural logic and spatial ambition simultaneously. In doing so, this graduation project somehow repositions Vitruvius' triad of firmitas, utilitas and venustas, to which I often times think, within a water-based and material-driven framework. Firmitas is no longer guaranteed by ground contact but must be designed through buoyancy, stability and force transfer. Utilitas expands toward adaptability within dynamic environmental and social conditions. Venustas is pursued not through spectacle, but through structural clarity and coherence. Layers of brand are innovated and adapted for and thoughout the project to this context and form a new architectural concept. Reflecting on this certain questions were unavoidable: how exactly did research steer the design, where did design redirect the research, how did my way of working affect the outcome, and what does this project actually add academically and socially?

Research & Design Interaction

The relationship between research and design was better described as iterative broadening rather than linear deepening. Every aspect researched opened a dozen others to dive into. Technical investigations into tidal variation, buoyancy, floating stability and horizontal force transfer did not remain abstract engineering studies; they progressively reshaped spatial logic. The recalibration of the urban grid provides a concrete example. Initially, a fine-grained 1.20 m grid was rigorously applied to guarantee adaptability and maintain control. Over time, it became clear that this micro-modulation constrained, rather than enabled architectural clarity. The grid is now redefined at a larger structural scale. This decision was not driven by time pressure but by conceptual maturation and technological and project specific understanding.

This shift now makes me think of the reflection question: "Can adaptability remain meaningful if the primary structural layer is permanently fixed?"

Within this project, adaptability proved to reside not in endless subdivision but in the distinction between a stable collective framework and flexible infill. The permanent pontoon structure forms the non-negotiable solid base layer, while programmatic infill elements remain adjustable within it. In that sense, adaptability is not reduced by a fixed structural layer; it becomes clearer because of it.

A second reflection question can be found with more relevance to the process: "Does designing stability as a collective framework redefine the role of the architect from form-maker to system-organizer?"

By prioritising the design of a structural and urban framework over isolated formal objects, forms and typologies, my interest shifted toward structuring conditions within which change can occur. This shift also connects to the AE studio's emphasis on systemic thinking, but more importantly it marked a personal change in how I approach the design.

What worked within my method was the continuous confrontation between spatial intention and technical limitation. Physical models and iterative testing ensured that massing, level differences and circulation were consistently checked against buoyancy limits and structural tolerances. What proved less effective was my tendency to extend research beyond the point at which it decisively informed design. At times, depth became a form of delay. In hindsight, clearer internal milestones for concluding research could have strengthened efficiency, without compromising rigor, and made the process more design driven.

Context, Ethics and Societal Positioning

The project addresses a discontinuity between functioning urban fragments in Rotterdam Zuid, particularly between Kop van Zuid, Rijnhaven, Katendrecht and Entrepothaven. As experienced by myself and translated through analyses in pictures, maps and sections; Spoorweghaven currently operates as an in-between area lacking spatial continuity. The proposal aims to transform this void, cold/chilly un human area, into both connective corridor and nodal destination.

However, the supposed societal implications of such a transformation requires critical reflection. A water-based waterfront district risks accelerating gentrification within a port city context already marked by socio-economic disparities. While the system incorporates typological diversity and multiple housing forms as well as ample amount of catering and shops, it cannot fully control market dynamics. As Habraken argues in his support–infill theory, which has a place on multiple levels in the design and research, the architect cannot determine future occupation or market dynamics through form alone. Acknowledging that market forces extend beyond architectural control is therefore not a deflection, but a recognition of the limits of design. Nevertheless, architectural decisions regarding scale, programmatic mix and accessibility influence who benefits and what possibilities are loose and which are fixed.

The ethical tension therefore lies in balancing urban improvement with inclusivity, without losing the Rotterdam sensation. If the project merely attracts a new demographic while displacing existing communities, its societal value becomes questionable. The ambition is to create a structure capable of accommodating diverse groups over time rather than prescribing a singular target audience. It should breathe the city's history and vibe and amplify what is already well designed and implemented. Whether this would succeed in reality remains uncertain and represents a limitation inherent to the speculative nature of a graduation project.

Academic Value

The material and fabrication research forms the academic core of the project. The exploration of geopolymer concretes and extrusion-based production is not presented as a finished technological solution but as a structured investigation into material behaviour, structural feasibility and architectural consequence. The research paper mapped the availability of Dutch waste streams, binder chemistry and curing conditions; within the design project these findings were translated into questions of mechanics, mass, buoyancy and connection detailing. In other words, the material was not applied to a predefined form, but the form was partially derived from material limits.

For each building component; floors, walls, columns, façade, roof and foundation, a deliberate evaluation was made regarding fabrication logic. Casting, extrusion and hybrid systems were compared in terms of precision, structural performance, reversibility and circular potential. Floors, for instance, require dimensional stability and predictable load transfer, making conventional casting rational in certain scenarios. Vertical cores and circulation elements function as long-term anchors within the building otherwise open floor plan. By contrast, façade components offer greater opportunity to incorporate other functions through additive manufacturing. This differentiation is not aesthetic experimentation for its own sake, but a test of how far extrusion production methods can operate within structural and regulatory and ecological boundaries.

The floating condition intensifies these questions. Weight distribution, centre of gravity and dynamic loading restrict formal freedom and force material efficiency. In that sense, the water-based context operates as a stress test for the academic hypothesis: can geopolymer-based buildings move beyond experimental prototypes and toward architectural application? Literally bridging the "Gap" which is now still there according to the Rilem training course I followed. The project does not provide a definitive answer, but it stages a coherent scenario in which material research, production logic and spatial hierarchy are interdependent rather than sequential. It showcases at least that architectural thinking broadens the scope of the implementation of this material.

The ecological dimension, while conceptually embedded, remains less developed than structural and material aspects. Although extrusion allows integration of habitat niches, porous geometries and water environment related detailing, these strategies have not yet been quantified in terms of biodiversity impact or lifecycle performance. This imbalance reflects a limitation within the current phase. Ecological ambition currently exceeds ecological validation. Further work would require collaboration with environmental specialists and measurable performance criteria rather than spatial speculation and design integration alone.

If there is academic value here, it lies more in the method than in the typology itself. It demonstrates how material research, hydrodynamic constraints and urban analysis can be synthesised into a coherent design framework, and how production logic can function as an architectural generator rather than a post-rationalisation. The academic value therefore lies in articulating a chain of reasoning from waste stream to structural module to urban block. Societally, it engages with themes of densification, circular construction and water-based urban expansion in the Dutch context, while acknowledging that technological optimism must be tempered by regulatory, ecological and economic realities.

Professional Development and Working Method

Throughout the whole process, I felt a tension between ambition and restraint. Early caution, driven by the desire to design only what seemed technically feasible and my tendency to overthink, performance pressure and perfectionism, I began with a more, limited exploration. Gradually and with push of my tutors, I allowed greater ambition while maintaining systemic coherence. This development reflects a transition from cautious student toward a more confident architectural thinker.

At the same time, the project exposed a weakness: difficulty in determining when research is sufficiently complete. The inclination to fully understand each layer occasionally delayed consolidation. In future projects, clearer prioritisation and phased decision-making would improve efficiency. Feedback from mentors played an important role in recognising this pattern. Repeated comments to "decide and move on" and to test proposals at a larger structural scale rather than refining micro-grids forced a recalibration of my working rhythm. The shift away from the 1.20 m grid toward a broader structural logic was not an isolated insight but the result of iterative critique and dialogue. Learning to incorporate feedback without diluting, but actually strengthening, the conceptual core has been a central development during this graduation process.

After the P4 most of the engineering questions regarding a polyvalent wall system incorporasting all layers of brand into one functioning façade system which is ultra light weight and made from one material class, was done. With this step, the bridging of the gap between material science and city scale design was finalised.

Transferability

The project is not transferable as a literal blueprint for floating urbanism. Its transferable value lies in its methodological structure: technical research leading to systemic abstraction, spatial testing and hierarchical recalibration. The essential transferable insight is the separation between permanent collective structure and adaptable infill.

In the end, this project feels more like a proposal that opens something up than a model that closes everything neatly. Which I find hard, it feels like it is not finished although for this moment it actually is. It shows one possible way of connecting material research, systemic thinking and urban analysis, but it leaves questions unresolved. I do not know how this framework would behave under real world conditions. Leaving that uncertainty visible feels more honest than pretending it is solved and is also part of this research and design.

Dutch Waste to Circular Structure:

Geopolymer Concrete as a Circular Architectural Engineering Material in the Dutch Context

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Master of Architecture - Architectural Engineering Graduation Studio

ABSTRACT

The cement industry is responsible for approximately 7-8% of global CO2 emissions, and total sector emissions have continued to rise since 2015. Geopolymer concrete (GPC), produced by alkali-activating aluminosilicate waste materials instead of calcining limestone, could reduce these emissions by 40-80% depending on mix design. The Netherlands generates large volumes of construction and demolition waste that could serve as GPC precursors, but whether these streams are available in consistent quality remains unclear. This research combines expert interviews, a RILEM training course, a site visit to Renewi, and a structured literature review to map Dutch material flows and benchmark GPC against OPC and UHPC. The findings confirm that sufficient precursor material exists, but that systematic improvements in demolition practice, quality control and regulatory frameworks are needed before GPC can be reliably deployed as a structural architectural material.

KEYWORDS: *geopolymer concrete, alkali-activated materials, circular construction, Dutch waste streams, architectural engineering*

1. INTRODUCTION

The cement industry accounts for approximately 7-8% of global CO_2 emissions, and total emissions from the sector have been rising since 2015 (IEA, 2023; Habert et al., 2020). Although global awareness of this problem has grown, reducing cement-related emissions is structurally difficult: roughly 60% of the emissions arise from the calcination of limestone, a chemical reaction that cannot be resolved through energy efficiency alone (Habert et al., 2020).

Geopolymer concrete offers a different approach. Rather than calcining limestone, GPC is formed by activating aluminosilicate-rich waste materials with an alkaline solution. Life cycle assessments report CO_2 reductions of 40-80% relative to OPC, depending heavily on the precursor and activator combination used (Cong et al., 2024; Habert et al., 2011). Many of the raw materials required could come from existing industrial and construction waste streams, which gives GPC particular relevance in circular economy contexts.

In the Netherlands, GPC is not yet part of mainstream construction practice. Contributing factors include the absence of dedicated Euronorm equivalents, limited familiarity among architects and structural engineers, and a gap between laboratory research and practical implementation. Given the country's significant demolition waste volumes and ambitious circular economy targets, the question is whether Dutch waste streams could form a consistent basis for GPC production, and under what conditions GPC could become a structurally and architecturally viable alternative. This paper suggests it can, provided that material flows are better managed, quality control is prioritised, and design knowledge is further developed.

2. METHOD

2.1. Research Context and Research Question

Concrete is the most produced building material in the world, with approximately 4 billion tonnes of cement produced annually (Habert et al., 2020). The Netherlands is not only a large consumer of concrete but also a significant generator of construction and demolition waste (CDW): in 2019, the Dutch construction sector had approximately 57 million tonnes of material inflows, while demolition activity in the Netherlands has been growing steadily in recent decades due to urban renewal and post-war building stock replacement (EIB & Metabolic, 2022; CBS, 2023). This combination - high concrete use, growing demolition rates, and an ambitious national circular economy agenda - makes the Netherlands a relevant context for exploring whether locally available waste streams could serve as precursors for geopolymer concrete.

At the same time, GPC remains largely absent from Dutch architectural practice. Design codes are lacking, knowledge in the profession is limited, and the material sits at the intersection of multiple disciplines that rarely communicate effectively. It is precisely this gap that this research aims to address: by examining the Dutch material context, comparing GPC's performance against existing benchmarks, and exploring the implications for architectural design and fabrication, the research aims to contribute to a better-informed integration of GPC in Dutch construction.

Research question: How can geopolymer concrete synthesised from Dutch industrial and construction waste streams be positioned as a circular building material, in comparison to Portland cement-based concrete and ultra-high performance concrete?

This overarching question is addressed through three sub-questions:

- **Sub-question 1 (Section 3.2):** What Dutch waste or residual material sources are suitable as geopolymer precursors or aggregates, and in what quantities and quality are they available within the Netherlands?
- **Sub-question 2 (Section 3.3):** What are the key environmental and mechanical differences between ordinary Portland cement concrete, ultra-high performance concrete, and geopolymer concrete?

- **Sub-question 3 (Section 4):** How can design strategies leverage the specific characteristics of regionally developed geopolymers, and what are the engineering implications for architectural applications?

2.2. Research Approach

This research is framed within the flow-stock-make framework of the Architectural Engineering studio at TU Delft. The three pillars - flow, stock, and make - intersect directly with the topic: the *flow* dimension concerns the material and waste streams that could supply GPC precursors; the *stock* dimension concerns the built environment as both the source of demolition waste and the context for future GPC application; and the *make* dimension concerns the fabrication methods, particularly prefabrication and 3D printing, that are most compatible with GPC's specific material behaviour. Together, these three pillars structure the research and make visible the connections between material science, circular economy logistics, and architectural design.

The research maps and evaluates Dutch waste-derived materials suitable for geopolymer synthesis, and establishes a comparative framework that analyses their material performance potential in relation to OPC and UHPC. This supports a more informed architectural integration of GPC, helping to address the current lack of formal design standards for geopolymer-based construction and thereby bridging the gap between innovative materials research and practical implementation in architecture.

By integrating five expert interviews - with professionals in certification (Ton van Beek, Kiwa Technology), structural engineering and infrastructure (Sonja Fennis, Rijkswaterstaat), concrete technology (Maiko van Leeuwen), demolition and waste processing (Martin Verweij; Peter Broere, Bond Recycling Nederland), and industry application (Mika Autio, CRH Finland) - with practice-based learning and knowledge acquired during a one-week RILEM TC 294-MPA training course on alkali-activated materials, and a site visit to Renewi's Building Waste Separation Plant, this research qualifies, validates, and benchmarks geopolymer concrete in the Dutch context. The RILEM training course included a significant body of recent and ongoing research that has not yet been formally published; these insights are referenced here as lecture contributions by the respective researchers. The site visit to Renewi provided first-hand operational insight into the current state of demolition waste processing in the Netherlands. Available published literature on BSA (bouw- en sloopafval) in the Netherlands is limited and largely dated; the most informative sources for current conditions are therefore the Renewi site visit itself and the expert interviews, which together offer a more representative picture of today's practice than the published reports alone.

3. Results

3.1. Material Introduction

Alkali-activated materials (AAMs), commonly referred to as geopolymers, form a class of inorganic binders produced by reacting aluminosilicate-rich precursors with an alkaline activator solution. Unlike Portland cement, whose hardening is based on a *crystallisation* process in which calcium silicate hydrate (C-S-H) crystals form and interlock, geopolymers harden through a *polymerisation* reaction that produces a three-dimensional aluminosilicate polymer network - structurally closer to plastics in its molecular architecture than to conventional cement (Provis & van Deventer, 2014). This fundamental difference in microstructure is at the root of many of GPC's distinct properties, from its chemical inertness to its thermal stability.

GPC relies on two main components:

1. **Precursors:** aluminosilicate-rich materials that contribute the reactive Si-O and Al-O bonds needed for polymerisation. They are characterised by their SiO_2, Al_2O_3, and CaO content, and by their degree of amorphousness. The more glassy or amorphous the precursor, the more reactive it tends to be.
2. **Activators:** alkaline solutions that dissolve the precursor and initiate polycondensation. The most commonly used activators are sodium hydroxide (NaOH), produced industrially via the chlor-alkali process from sodium chloride, and sodium silicate (Na_2SiO_3, or waterglass), produced by fusing quartz sand with soda ash at high temperatures. Alternative activators include sodium carbonate (Na_2CO_3), sodium sulfate, and recovered alkaline sources such as mineral wool leachate, which are explored for their lower environmental impact (Bernal, 2025; Luiz-Miranda, 2025).

Precursors are often classified using ternary diagrams based on their SiO_2-Al_2O_3-CaO composition. Figure 1 provides an overview of the wide range of potential precursor sources and their relative positions in this system, adapted from Bernal (2025) and Chen et al. (2023). The diagram makes clear that the precursor landscape is not limited to a few industrial by-products, but spans a large variety of waste materials from different sectors.

Conventional precursors - blast furnace slag (BFS) and fly ash (FA) - are the most studied and best understood, but their availability in the Netherlands is declining: BFS supply is falling as electric arc furnaces gradually replace blast furnaces in steelmaking, and FA has contracted sharply with the phase-out of coal-fired power plants (Luiz-Miranda, 2025). This decline in the two most studied precursors is, counterintuitively, an argument *for* geopolymer's long-term potential rather than against it. The very versatility of the precursor landscape - illustrated by Figure 1 - means that as conventional sources diminish, other waste streams, including CDW fines, incinerator bottom ash, metallurgical slags, and agro-industrial residues, can potentially step in. Properties can be combined by blending precursors, the total accessible waste volume across all streams is very large, and some streams are growing rather than declining. However, this flexibility comes with a condition: quality must be guaranteed. Non-conventional precursors are inherently more variable in composition and reactivity than FA or BFS, and this variability requires careful processing, testing, and quality control before they can be reliably used in structural applications (Bernal et al., 2016; Athira et al., 2021).

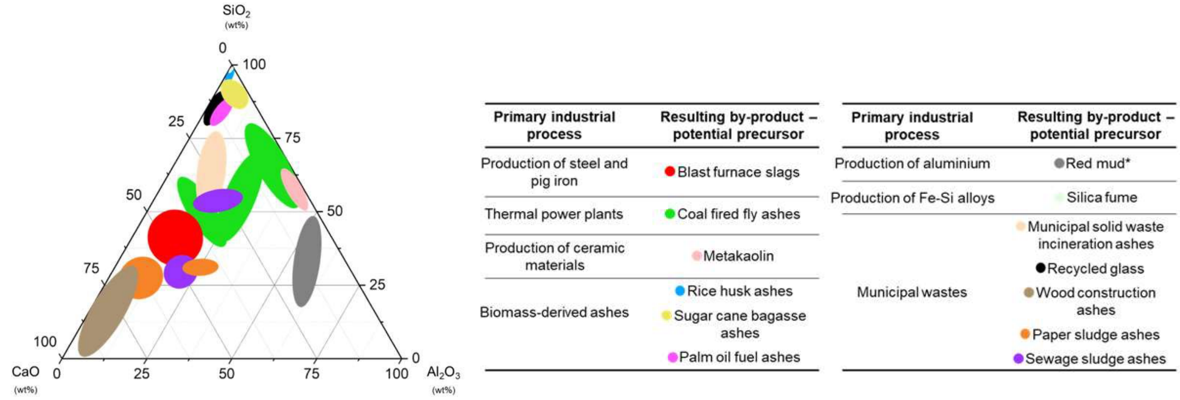

Figure 1. Ternary classification diagram of geopolymer precursors. The broad distribution of points illustrates the wide variety of potential raw material sources.

The diagram shows the compositional space of geopolymer precursors. Fly ash and blast furnace slag occupy well-known positions, while construction demolition waste, bottom ash, and various metallurgical slags occupy a broad range of positions, illustrating the diversity of potential raw material sources. High-CaO systems (right side) produce harder-setting, calcium silicate hydrate-enriched binders; high-SiO2/Al2O3 systems (left) produce more classic geopolymer networks. Source: adapted from Bernal, S.A. (2025). Non-conventional precursors in alkali-activated materials. RILEM TC 294-MPA Training Course; Chen et al. (2023).

3.1.1. Environmental impact

The environmental picture of GPC is promising but nuanced. Rather than pointing to a single CO_2 reduction figure, it is more accurate to say that GPC offers significant flexibility in its environmental footprint, precisely because of the diversity of available precursor streams. The mix design combinations required to optimise a GPC for a specific application - varying precursor ratios, activator types, and curing conditions - also determine the environmental outcome. Some combinations are extremely low-carbon: when precursors are derived from industrial waste that would otherwise have been landfilled, GPC benefits from a double CO_2 advantage - the avoided emissions from the precursor's waste disposal, combined with the substitution of clinker. Others, particularly those using large volumes of sodium silicate activator produced from virgin silica, can have a higher environmental footprint that substantially reduces the benefit (Habert et al., 2011).

Life cycle assessments consistently show reductions of 40-80% in CO_2 relative to OPC for optimised mixes, with the wide range reflecting the sensitivity to activator choice and sourcing context (Cong et al., 2024; Habert et al., 2011). Exact calculations are therefore difficult to make in advance without a specific precursor and activator specification, and comparisons between studies should be interpreted with this in mind.

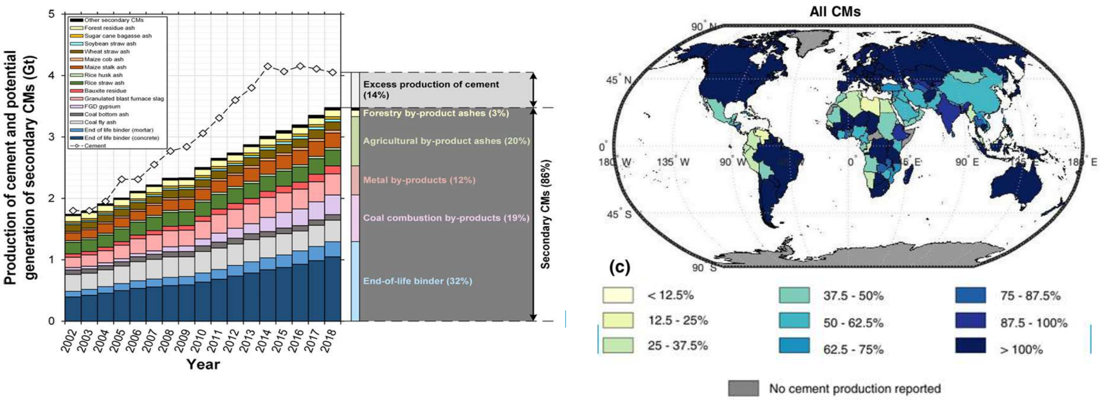

Figure 2. Estimated global CO2 reduction potential through cement substitution with secondary materials (Shah et al., 2022).

This figure shows the potential annual global CO2 reductions achievable through cement substitution with secondary cementitious materials, estimated at up to 1.3 Gt CO2/yr. It contextualises the scale of the opportunity that GPC and other AAMs represent within the broader decarbonisation agenda. Source: Shah, I.H. et al. (2022). Cement substitution with secondary materials can reduce annual global CO2 emissions by up to 1.3 gigatons. Nature Communications, 13(1), 5758.

3.2. Material Flows: Dutch Waste Streams as GPC Precursors

The potential for GPC production in the Netherlands is inherently linked to the availability and quality of local precursor materials, which can be derived from industrial and construction waste streams. These flows are shaped by national recycling infrastructure, regulatory goals, and the practices of the demolition and materials processing sector.

According to EIB & Metabolic (2022), the Dutch construction sector generated approximately 57 million tonnes of material inflows in 2019, of which only 26% could be matched with outflows from demolition or renovation. Asphalt recycling demonstrates what is possible when logistics and incentives align, reaching reuse efficiencies of up to 79%. Concrete and mixed rubble streams show significantly lower closed-loop rates of 59% and 51% respectively, and only 4.5% of all recycled aggregates are used in structural concrete applications (BRBS Recycling, 2015).

Figures 3 and 4 show the Sankey flow diagrams for building waste (BA) in the Netherlands for the 2020 market situation and the 2025 target respectively. The diagrams reveal three key structural insights. First, the dominant current destination for concrete demolition waste is low-grade applications such as road base and fill material - high-grade recycling, including as aggregate for structural concrete or as GPC precursor, represents a small fraction of total throughput. Second, the 2025 target - which identifies "slim breken" (smart crushing) and selective demolition as the main levers - envisioned a substantial shift toward higher-value material flows, including increased granulate quality for structural reuse. It should be noted that the 2025 target date has now passed; no updated flow data are available to assess whether the targets were met. Third, and critically, the gap between the 2020 baseline and the 2025 ambition cannot be closed by better processing technology alone. The root cause is demolition practice.

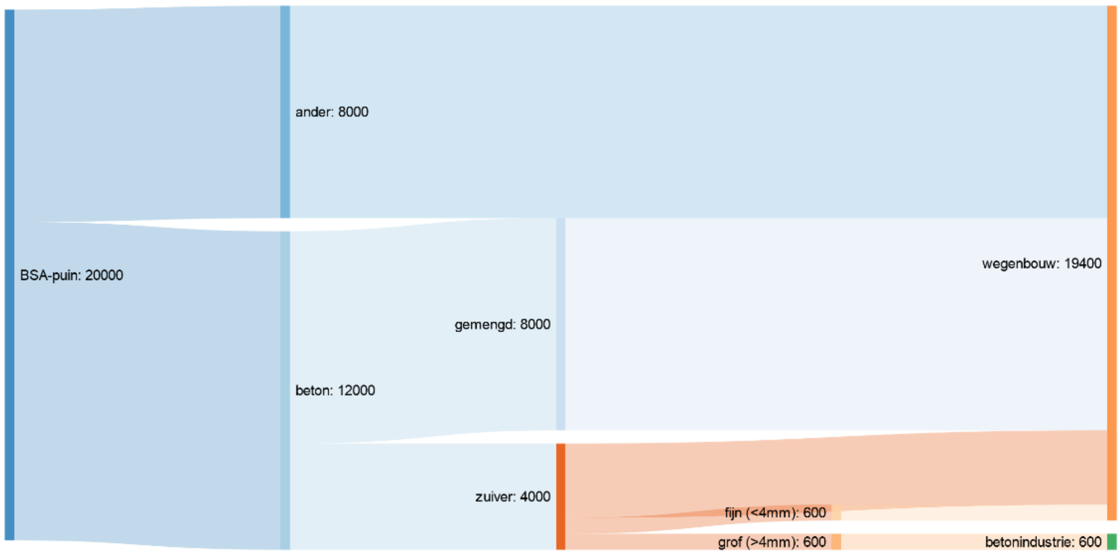

Figure 3. Current BA material flows in the Netherlands (2020). Most material ends up in low-value applications.

Current material flows of Dutch building waste (BA). The majority of material flows to low-grade end uses (road base, fill). The fraction reaching high-grade structural concrete reuse is very small. Concrete granulates (BSA-granulaten) for structural use represent only a minor fraction of the total stream. Source: Sankey doelstellingen hergebruik BA (2024).

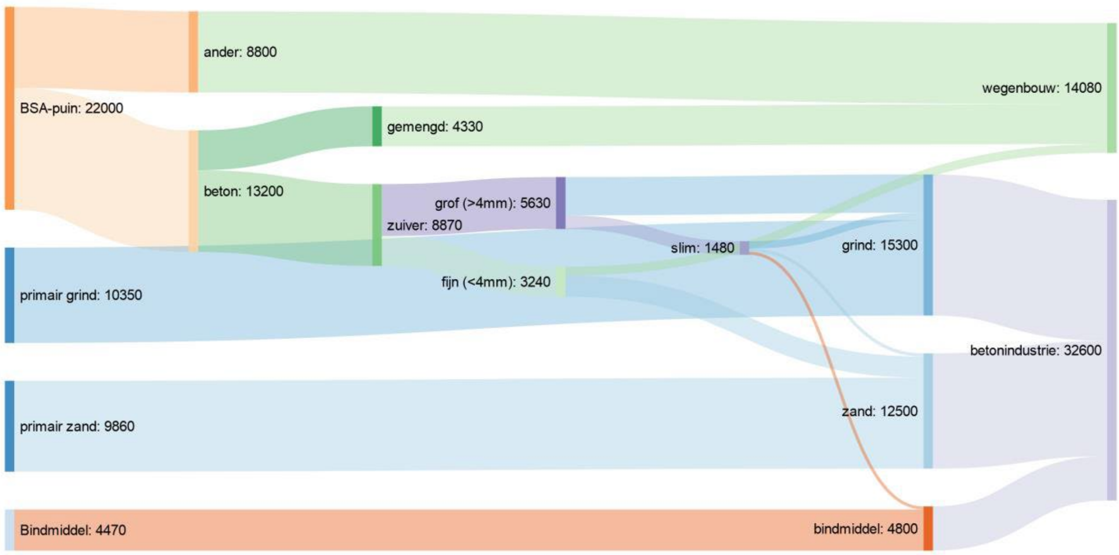

Figure 4. Target BA material flows for 2025.

Target material flows for 2025, achieved through selective demolition and smart crushing.Smart crushing and selective demolition are the key levers for shifting material to higher-value applications. The "resultante primair" shows the remaining virgin material input after circular substitution is maximised. A significantly larger fraction of granulates would reach structural-grade quality. Note: 2025 has passed and no verification data are yet available. Source: Sankey doelstellingen hergebruik BA (2024).

Ronald Reyersen, concrete recycling supervisor at Renewi, explained during the site visit that approximately 20% of the incoming concrete stream is currently usable in their high-grade processing chain (Reyersen, site visit Renewi, 2025). Importantly, this is not primarily a capacity or technology problem: Reyersen indicated that with adjusted demolition practice - more selective, separation-oriented disassembly - this figure could realistically reach 80%. The current low usability rate results from buildings being demolished in bulk, causing materials to become mixed and inseparable before they reach the recycling facility. This is consistent with Martin Verweij's observation (Interview 3) that demolition contracts are structured around speed and cost rather than material recovery, and with Ton van Beek's point (Interview 1) that current Dutch sorting protocols do not prioritise geopolymer-suitable fractions.

CDW, specifically stone building rubble, is the key candidate for secondary material sourcing. However, Maiko van Leeuwen (Interview 2) and Martin Verweij (Interview 3) both emphasise that CDW is far from a homogeneous stream: historical building practices, inconsistent demolition protocols, and insufficient source separation create high variability in composition and quality.

3.2.1. The potential role of chemical inertness

One property of geopolymer concrete that has particular relevance for the Dutch waste context is its high chemical inertness - the polymerised aluminosilicate matrix is significantly more resistant to chemical attack than calcium silicate hydrate in OPC (Skariah et al., 2022). This suggests that GPC may be able to tolerate a higher degree of contamination in its aggregate fraction without the same loss in performance that would occur in OPC. In principle, this could allow waste streams currently unsuitable for use as aggregate in OPC concrete to be used in GPC applications. However, it is important to note that this tolerance has limits, and that the current shortcomings in demolition waste separation are still serious: better sorting remains important and would always improve performance. GPC's inertness provides a degree of additional resilience, not a substitute for good practice.

3.2.2. Fine fractions and slib

A specific fraction highlighted during the Renewi site visit is the ultra-fine concrete slib - slurry residue from wet processing - which currently has no established valorisation pathway. It cannot be used as conventional aggregate, and its fine particle size limits other applications. At the same time, Mika Autio (Interview 5) noted that research on reactivating cement fines and fine stony particles as GPC precursors is ongoing and shows some promise. Even a 5-10% replacement contribution from such reactivated fines would represent a large absolute volume given the scale of the sector (Autio, Interview 5). This opens a potential circular pathway specific to the Netherlands' high demolition throughput, provided processing and quality-testing infrastructure is developed.

3.2.3. End-of-life design and future recyclability

A broader implication of the findings is that the ease of future separation should be prioritised at the point of material introduction. When new buildings are designed and built with GPC, their end-of-life should be considered from the outset: structural elements should be detailed and connected in ways that allow selective disassembly, and material passports should identify GPC elements for future recyclers. This is consistent with the Betonakkoord and KCI circular ambitions, but requires active engagement from the design profession rather than relying solely on processing innovation at the end of the chain.

3.2.4. OPC and GPC in the transition period

An important practical concern for the transition from OPC to GPC is the question of whether the two materials can coexist in demolished rubble and whether cross-contamination poses a problem. At aggregate level, the risk is relatively manageable: the aggregate fraction is largely chemically inert regardless of the original binder, and GPC's alkaline curing environment may even improve the surface properties of recycled OPC aggregate. At the fines and paste level, however, calcium introduced from residual OPC paste can alter the geopolymerisation reaction chemistry, shifting the product toward a hybrid calcium-silicate system with different properties (Ton van Beek, Interview 1). Conversely, recycled GPC fines in OPC systems are less well understood. For the transition period, clear identification and registration of GPC structural elements - in material passports or digital building records - is therefore important to allow future separation and targeted reuse.

3.2.5. Systemic barriers

Beyond the physical flow challenges, several systemic constraints limit the valorisation of Dutch waste streams for GPC. Ton van Beek (Interview 1) highlighted the regulatory paradox: materials that lose their "waste" classification in order to be reused in construction are thereby no longer counted as a circular contribution by concrete producers. This actively disincentivises high-value valorisation. Peter Broere's reports (BRBS Recycling, 2015; SGS Intron, 2005) project a 20% increase in construction waste volumes by 2025 relative to 2005 levels, yet only a marginal fraction is expected to reach GPC-suitable quality without aligned policy, sorting technology, and processing practice.

3.3. Benchmark Comparison: GPC vs OPC and UHPC

To evaluate GPC's structural viability, this section benchmarks its performance against ordinary Portland cement concrete - specifically CEM III/B, the most widely used binder in Dutch structural construction - and ultra-high performance concrete (UHPC). The comparison draws on the published literature and unpublished research presented during the RILEM TC 294-MPA training course (2025).

3.3.1. Compressive Strength

GPC produced from slag- or fly ash-based precursors typically achieves compressive strengths of 30-80 MPa (Masi, 2025; Duxson et al., 2007), which comfortably meets the most common Dutch structural concrete classes (C30/37 to C50/60). CEM III/B, the standard Dutch structural binder, is classified at 32.5-42.5 MPa, placing conventional GPC in the same range or above (BMN, 2024; Rijkswaterstaat, 2023). UHPC exceeds 120 MPa through optimised particle packing and fibre reinforcement (Li et al., 2020).

GPC produced from non-conventional precursors - CDW fines, bottom ash, mixed slags - shows more variable compressive strengths, typically in the range of 15-50 MPa, depending on precursor reactivity, blend composition, and activator dosage. These mixes have fewer published datasets, making reliable prediction more difficult at this stage (Bernal et al., 2016; Athira et al., 2021).

3.3.1.1. The role of water content

A lower water-to-binder ratio in GPC actually improves its performance more directly than in OPC. In OPC systems, water participates in the hydration reaction; in GPC, water serves only as a solvent medium and does not become chemically bound. Excess water therefore fills pore space that remains after evaporation, reducing density and creating pathways for shrinkage and chemical ingress. Reducing the water content in GPC is therefore beneficial from a mechanical and durability standpoint. That said, standard water quantities are entirely workable and produce acceptable results; a somewhat elevated porosity simply results in a modest reduction in peak compressive strength. The critical point is that the curing process requires careful monitoring, since moisture loss during early setting significantly affects the final properties. This is one of the key reasons why prefabrication is advantageous for GPC: a controlled factory environment allows curing temperature and humidity to be managed precisely, minimising variability and maximising performance.

Where the reduced water ratio creates a challenge is in workability and flowability of the fresh mix: fresh GPC at a low water content can be stiff and difficult to place in complex formwork. This is discussed further in Section 4.

3.3.2. Modulus of Elasticity

GPC's elastic modulus is generally 5-15% lower than OPC concrete of equivalent compressive strength class. Masi (2025) reports 25-35 GPa for slag-based AASC, compared to 30-40 GPa for equivalent OPC at 28 days. Non-conventional precursor GPCs show larger variability and generally lower values, with limited published data. For structural design, a slightly reduced elastic modulus implies greater deflection under service loads, which requires attention in long-span slabs and facade elements where deflection serviceability governs. UHPC reaches 45-55 GPa (Tran et al., 2025).

3.3.3. Tensile, Flexural Strength and Bond to Reinforcement

Without fibre reinforcement, GPC shows splitting tensile strengths of 3-5 MPa and flexural strengths of 4-8 MPa - comparable to OPC of the same compressive class (Rossi et al., 2025; Provis & van Deventer, 2014). With steel or polymer fibres, GPC can surpass OPC in post-cracking behaviour and energy absorption, due to the crack-bridging effect of fibres combined with GPC's typically denser matrix (Ahmed et al., 2020; Bezemer et al., 2023).

Bond to steel reinforcement is one of GPC's clear advantages over OPC: fly ash- and slag-based GPCs show comparable or improved bond strengths, attributed to a denser interfacial transition zone (ITZ) that enhances stress transfer and reduces slip (Lukovic, 2025; Al-Azzawi et al., 2018). This means standard Eurocode 2 reinforcement detailing can generally be applied without major redesign, which is an important practical benefit for market adoption.

3.3.4. Fire Resistance

GPC significantly outperforms OPC in fire resistance. While OPC concrete begins to lose meaningful strength above approximately 300°C as C-S-H dehydrates and the matrix deteriorates, GPC retains more than 90% of its compressive strength at temperatures up to 800°C (Skariah et al., 2022; Provis & van Deventer, 2014). This is a direct consequence of GPC's aluminosilicate polymer network, which is thermally stable at much higher temperatures than the calcium silicate phases in OPC. For architectural applications involving fire safety requirements - particularly structural facades, industrial buildings, or elements near potential ignition sources - this is a meaningful performance advantage that could justify GPC use even where other properties are equivalent to OPC.

3.3.5. Chemical Resistance

GPC's resistance to acids, sulfates, and chlorides consistently surpasses that of OPC (Skariah et al., 2022; Shi et al., 2011). The aluminosilicate matrix is far less soluble than OPC's calcium silicate hydrate under acidic or sulfate-rich conditions: life cycle assessments of GPC in sulfuric acid environments report CO_2 emission reductions of 94-97% relative to OPC when service life is accounted for, because GPC elements simply last much longer under aggressive exposure (Cong et al., 2024). Non-conventional precursor GPCs also generally show high chemical resistance, though this varies with precursor chemistry and requires verification for specific mixes.

3.3.6. Durability and Carbonation

Long-term deflection and crack development in GPC beams are broadly comparable to OPC members of equivalent design class (Prinsse et al., 2020). Drying shrinkage and carbonation susceptibility can be higher depending on mix design and curing conditions, and both are related to the pore structure and chemistry of the alkali-activated binder.

Carbonation in GPC is a complex topic that cannot be fully characterised based on current knowledge. The rate and mechanism of carbonation depend heavily on precursor composition: high-calcium systems (slag-rich) show different carbonation behaviour from low-calcium fly-ash-based systems, and mixes using non-conventional precursors have almost no long-term carbonation data at all. It is important to note that most published carbonation test results for GPC have been obtained using accelerated test methods developed for OPC, which may not represent real-world GPC behaviour accurately (Zhang et al., 2024; Austroads, 2018). Further research - with test protocols specifically tailored to GPC chemistry - is needed before robust conclusions can be drawn. This is flagged as one of the key open questions in the conclusions.

3.3.7. Benchmark

Table 1 summarises the benchmark comparison, including a column for non-conventional precursor GPC systems where data are available. Green cells indicate parameters where GPC outperforms OPC.

Table 1. Benchmark comparison of OPC (CEM III/B), GPC (slag/FA-based), GPC (non-conventional precursors), and UHPC.

Parameter	**OPC (CEM III/B NL)**	**GPC (slag/FA-based)**	**GPC (non-conventional precursors)**	**UHPC**
Compressive strength	20-60 MPa (CEM III/B: 32.5-42.5 MPa)	30-80 MPa	15-50 MPa (variable)	120-150 MPa
Modulus of elasticity	30-40 GPa	25-35 GPa	20-30 GPa (limited data)	45-55 GPa
Tensile / flexural (plain)	2-4 / 3-6 MPa	3-5 / 4-8 MPa	2-4 / 3-6 MPa (limited data)	- / 15-25 MPa (fibres)
Bond to reinforcement	Standard	Comparable or better (denser ITZ)	Limited data, likely comparable	High
Fire resistance	Loses strength >300°C	**Retains >90% at 800°C**	**Generally good, precursor-dependent**	Good

Chemical resistance(acid, sulfate, chloride)	Moderate	**High, outperforms OPC**	High to very high	High
Carbonation resistance	Moderate to good	Moderate, mix-dependent	Variable, largely unknown	Very low (dense matrix)
Durability (long-term track record)	Proven (>100 yr)	Promising / variable	Very limited data	Excellent
Prefab suitability	Good	**Very good (fast set; controlled cure)**	Good with quality control	Good

Sources: BMN (2024); Duxson et al. (2007); Li et al. (2020); Lukovic (2025); Masi (2025); Prinsse et al. (2020); Provis & van Deventer (2014); Rijkswaterstaat (2023); Rossi et al. (2023); Skariah et al. (2022); Tran et al. (2025); Zhang et al. (2024).

4. Discussion and Conclusions

4.1. Prefabrication and 3D Printing as Primary Application Contexts

GPC's mechanical characteristics and practical constraints converge on prefabrication as its most natural application context in the Dutch setting. The fast set times of FA-rich mixes - which would be a logistical obstacle in traditional on-site casting - become an advantage in a factory environment where casting cycles are controlled and transport distances are zero. Prefabrication also allows curing temperature and humidity to be managed precisely, which directly improves GPC's mechanical performance and consistency; as Ton van Beek noted (Interview 1), industrial-scale production of GPC is feasible if mix designs are standardised and quality is monitored. Maiko van Leeuwen (Interview 2) and Sonja Fennis (Interview 4) both pointed to the elimination of transport time as a practical advantage, since GPC mixtures do not require delayed setting for transport in a prefab context.

An additional consideration is that GPC production requires somewhat stricter chemical safety protocols than conventional OPC work, because the alkaline activators - sodium hydroxide and sodium silicate - are more aggressive than standard cement slurry. A controlled factory environment is well suited to managing this: adequate ventilation, protective equipment, and clearly separated component storage are more easily maintained in a precast facility than on a traditional construction site. As Mika Autio (Interview 5) noted, factory-controlled GPC production in Finland has demonstrated that consistent quality is achievable under these conditions.

3D concrete printing is another production method where GPC's specific properties are particularly compatible. The fast-setting behaviour of high-FA mixes is well suited to layer-by-layer deposition, since each deposited layer gains green strength quickly and supports subsequent layers without slumping. Researchers at Ghent University (De Schutter, 2025) developed a two-component extrusion mixing head in which the precursor slurry and the activator are kept separate until they are mixed at the nozzle, just before extrusion. This eliminates premature hardening in the machine and the supply lines - a major operational problem with fast-setting GPC in conventional single-component printers. The result is a printing process that behaves more like FDM (fused deposition modelling) than conventional LDM (large deposition modelling): a bead is deposited that begins hardening almost immediately at the point of extrusion, enabling tighter geometric control. This opens up the use of 6-axis robotic printing, which is not limited to horizontal layer deposition and can produce overhangs, complex geometries, and structurally optimised forms with a much greater degree of architectural freedom than conventional concrete printing allows.

Carbonation and reinforcement durability require careful attention in structural GPC elements, particularly for atmospheric exposure classes. The specifics depend heavily on the precursor system used, and current test methods - developed for OPC - may not accurately predict GPC behaviour. This warrants further investigation and should be addressed through geometry, mix design, appropriate cover depths, and material-specific testing rather than through rigid adherence to OPC-derived rules.

4.2. Structural Design Considerations

GPC produced from slag- or fly ash-based precursors can achieve compressive strengths that meet or exceed Dutch standard classes (C30/37 and higher). The slightly reduced elastic modulus (25-35 GPa vs 30-40 GPa for OPC) requires attention in deflection-governed design, but remains within ranges that standard Eurocode checks can accommodate with minor adjustments. Bond to conventional steel reinforcement is at least comparable to OPC, supporting the use of standard detailing without major redesign (Lukovic, 2025).

Where GPC requires additional attention: mix design is more sensitive to precursor variability than OPC, long-term creep data are limited, and carbonation behaviour is not yet well characterised for all precursor systems. The "design assisted by testing" provisions of Eurocode already provide a normative pathway for novel materials - as Ton van Beek (Interview 1) explained, a wall tested to failure tells you more reliably what it can do than a calculated model derived from OPC assumptions. Accelerating the use of this design-by-testing approach is one of the most practical ways to bring GPC into structural practice, since it reduces dependence on material-specific standards that do not yet exist.

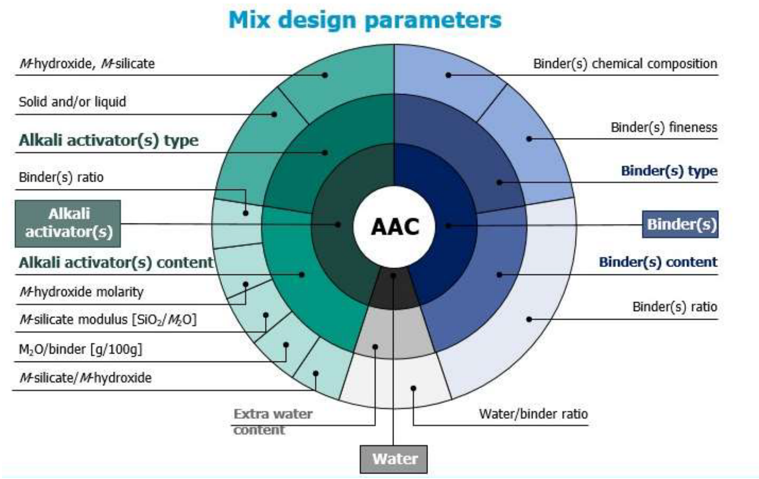

Figure 5. Mix design parameters for AAM and their effect on structural properties

This figure shows the key mix design variables in alkali-activated materials (precursor type and blend, activator type and modulus, water content, curing temperature and duration) and their combined influence on structural performance. It illustrates why GPC cannot be characterised by a single set of values and why tailored mix design is essential for each application context. Source: Rossi, L. et al. (2023). Future perspectives for alkali-activated materials: from existing standards to structural applications. RILEM Technical Letters, 7, 159-177.

4.3. Where GPC's Specific Strengths Lie

Based on the benchmark analysis and expert interviews, GPC's competitive advantages over OPC are most pronounced in three areas:

- **Chemical and thermal resistance:** GPC significantly outperforms OPC in resistance to acids, sulfates, chlorides, and elevated temperatures. These properties make it particularly well suited to chemically aggressive and thermally demanding service environments.
- **Circularity potential:** GPC is the only structural concrete binder that can be synthesised entirely from waste streams, including materials that currently have no valorisation route. This positions it uniquely within the Dutch circular economy agenda.
- **Digital fabrication compatibility:** Fast-setting behaviour and the availability of two-component extrusion systems make GPC well suited to advanced 3D printing methods, offering architectural and structural freedom that exceeds what conventional concrete printing currently allows.

The path from these advantages to widespread adoption runs through standardisation, pilot projects, and cross-disciplinary knowledge sharing. Tests and assessment methods should be tailored to GPC's specific chemical mechanisms rather than transplanted from OPC practice; OPC-based carbonation tests, compressive strength protocols at 28 days in water, and modulus models all carry assumptions that do not hold for geopolymer systems (Zhang et al., 2024; Ton van Beek, Interview 1). Developing GPC-specific test protocols and connecting them to the existing Eurocode framework via design-assisted-by-testing provisions is therefore a priority for the field.

4.4. Answer to the Research Question and Conclusions

Returning to the research question - how can geopolymer concrete synthesised from Dutch waste streams be positioned as a circular building material, in comparison to OPC and UHPC - the findings support the following conclusions:

1. **Dutch waste streams can support GPC production, but require systemic improvement.** Sufficient volumes of BFS, CDW fines, bottom ash, and emerging metallurgical slags exist to support GPC production at scale. The binding constraint is not material availability but quality and consistency: current demolition practice mixes materials that should be kept separate, and about 20% of incoming concrete at a best-in-class facility is currently usable in high-grade processing (Reyersen, site visit Renewi, 2025). With selective demolition, this could reach 80%. Regulatory paradoxes in waste classification and insufficient quality-sorting incentives compound the problem.
2. **GPC is mechanically viable for Dutch structural applications.** Compressive strengths of 30-80 MPa (slag/FA-based systems) meet the most common Dutch structural concrete classes. Bond behaviour, fire resistance, and chemical resistance are areas where GPC is equal to or better than OPC. Elastic modulus and long-term carbonation require careful design attention but are manageable within existing engineering practice. Non-conventional precursor mixes offer less predictable performance and require more testing.
3. **GPC occupies a distinct performance niche.** GPC is not a direct substitute for OPC, and is not trying to compete with UHPC. Its competitive advantages - chemical resistance, circular sourcing, and digital fabrication compatibility - define a specific set of applications where it outperforms alternatives: chemically aggressive environments, prefabricated circular building components, and 3D-printed structural elements with complex geometries.
4. **Architectural engineering is the missing bridge to practice.** The gap between laboratory GPC research and built application is not primarily a technical one - it is systemic. Architects and structural engineers who can integrate material knowledge, fabrication logic, regulatory navigation, and design ambition are the key actors needed to bring GPC from pilot project to practice. Accelerating the adoption of design-assisted-by-testing approaches within Eurocode, as advocated by Ton van Beek (Interview 1), would significantly lower the barrier to entry and allow GPC to be specified on real projects without waiting for dedicated material standards.

Open questions for further research: Carbonation behaviour in non-conventional precursor systems requires dedicated investigation with GPC-appropriate test methods. Long-term creep data for Dutch-sourced precursor mixes are lacking. The recyclability of GPC at end of life - particularly when mixed with OPC rubble - needs systematic study to underpin the circular economy claims made for the material. Finally, the compatibility of two-component 3D printing methods with non-standard precursor blends is an open design and engineering question that bridges fabrication and materials science.

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6. APPENDIX

A. Glossary

AAM (Alkali-Activated Material): Broad class of inorganic binders produced by activating an aluminosilicate precursor with an alkaline activator. Encompasses geopolymers and calcium-containing systems such as alkali-activated slag.

Activator: Alkaline solution used to dissolve and repolymerise the precursor. Most common: NaOH (sodium hydroxide) and Na2SiO3 (sodium silicate / waterglass).

Aggregate: Granular filler material (sand, gravel, crushed stone) making up 60-80% of concrete volume. Recycled aggregates (RA) from CDW are a key circular resource.

BA (Bouw- en sloopafval / Bottom Ash): Construction and demolition waste or incinerator bottom ash. Context-dependent in this paper; both are discussed as potential GPC precursor sources.

Betonakkoord: Dutch national industry agreement (2018) committing the concrete sector to a 30% CO2 reduction by 2030 and 100% circular concrete by 2050.

BFS / GGBFS: Blast furnace slag / ground granulated blast furnace slag. Conventional GPC precursor with high reactivity. Availability in the Netherlands is declining.

CDW (Construction and Demolition Waste): Waste from demolition, renovation, or construction. Largest waste category by volume in the Netherlands; includes concrete rubble, brickwork, and mixed fractions.

CEM III/B: Portland blast furnace cement with 66-80% GGBFS. Most commonly used in Dutch structural construction; strength class 32.5-42.5 MPa.

FA (Fly Ash): Fine residue from coal-fired power stations. Conventional GPC precursor. Availability in the Netherlands has declined sharply with the phase-out of coal power.

GPC (Geopolymer Concrete): Concrete in which the binder is an alkali-activated aluminosilicate material rather than Portland cement clinker. Used in its broadest sense here.

ITZ (Interfacial Transition Zone): The microstructurally distinct zone between aggregate and binder paste. GPC typically forms a denser ITZ than OPC, improving bond to reinforcement.

LCA (Life Cycle Assessment): Methodology for quantifying environmental impacts across a product's full life cycle, from raw material extraction to end of life.

OPC (Ordinary Portland Cement): Most produced cement type globally. Manufactured by calcining limestone at ~1450 C. Responsible for ~7-8% of global CO2 emissions.

Precursor: Aluminosilicate-rich material that reacts with an activator to form the GPC binder. Examples: fly ash, slag, metakaolin, CDW fines.

Slim breken (Smart crushing): Selective demolition and crushing strategy that aims to produce higher-quality, more consistent material fractions from CDW for high-grade reuse.

TRL (Technology Readiness Level): Scale from 1 (basic principles) to 9 (proven in operational environment) indicating the maturity of a technology. Slag-based GPC for precast: TRL 6-7.

UHPC (Ultra-High Performance Concrete): Dense, high-strength concrete (>120 MPa) based on Portland cement with silica fume, very low w/c ratio, and fibres. Excellent durability, high cost. Used in bridges, thin-shell structures, facade panels.

w/b ratio: Water-to-binder ratio. Lower w/b improves GPC strength and density; excess water does not react and creates porosity.

B. Expert Interview Transcripts

The following appendix contains the full transcripts of the five expert interviews conducted between January and February 2025. Interview 5 (Mika Autio, CRH Finland) was conducted in English. Interviews 1-4 were conducted in Dutch; translations into English have been prepared with the assistance of AI transcription tools (a combination of manual notes, recorded audio, and AI-supported transcription and translation was used for all interviews). The transcripts have been reviewed and edited for accuracy by the author.

Interview 1: Ton van Beek, Kiwa Technology (certification)

[Full transcript - see submitted document. Original language: Dutch. English translation below.]

Interview Transcript 1 – Ton van Beek

Sam Meeuwis: This interview is for my graduation research for my master's degree at TU Delft. I am graduating in the Architecture track and I am currently enrolled in a studio called Architectural Engineering. Within that track, you are given a great deal of freedom in what you want to research and what your subsequent design — which follows from that — will be. My research began from a fascination with geopolymers, which I had heard about before. While materials science is not strictly the Architectural Engineering side of things, the implications of how you deal with it as a designer, what production methods are available, how those can reach the market, and how you as an architect can steer that and be a driving force — all of that is.

That is why I reached out to you after the symposium. Because when we talk about certification, about how construction innovations develop into actual products and how you can bring them to market, you are the right person to speak to.

I currently have a number of interviews scheduled, of which this is one. The intention is for it to be an in-depth interview. That means we hold a fairly open conversation in which I try to steer things a little towards the answers I am looking for. That way we arrive at a fairly nuanced and somewhat deeper conclusion than if it were only closed questions with short answers.

The set-up of my research is that I will be investigating what methods exist in the Netherlands to produce geopolymers. In the first instance I am genuinely looking at waste streams — both from industry and from construction. As an architect, it is naturally interesting to look at construction because you can then recycle construction rubble and the like as aggregate and close the loop in construction. But also because there are a great many building materials from which raw materials for geopolymers could be made. You can see that, for example, with products like Wool2Loop, which does this using mineral wool. There you very quickly see that there are a great many obstacles in the way.

What do you think are currently the biggest gaps for geopolymer concrete in the Netherlands?

T. van Beek: I am, of course, from the certification side of things, so the finger is always pointed at regulation. A small piece of research was recently done into this: is regulation the problem? That turned out not to be the main problem.

Regulation is always a threshold. That is what we make it for. You have to jump through a hoop in order to be applied. That hoop is also a barrier, but it is not the biggest barrier. What I see is that a great many of these kinds of companies are primarily focused on getting the technology sorted as quickly and as well as possible, in order to obtain a product that can be used in the market. That is sometimes called the technical analysis level. They are completely focused on that, and then the technology is fully ready to go to market — but alongside that, you still have a number of other aspects, which you call the market-readiness level, the stakeholders-readiness level, or the acceptance-readiness level.

Besides the technology, you also need to organise other things. It is not just a matter of seeing whether the powder hardens. It is also a question of: does the architect even want to work with your product? Your technology may be sound, but aesthetics rarely feature in the technology.

Once you can scale all of that up, you are purely left with: do you actually want to and can you build a factory for it? Do you have the raw materials you need in sufficient quantities to produce at scale? Because to make money, you still need to produce some tonnage. And then you also need tonnage — if you are talking about waste — of waste material that you can convert so that it becomes a product. It is usually also not the case that one tonne of waste yields one tonne of binder. It is usually tonnes of input and very few tonnes of output. So to get it to market: you have already been through an entire research trajectory, it also takes years to get it technically right, and then you still have to do that scale-up to build a factory for it.

That is where you often also see the problems — or at least the difficulties. What they have done in practice, for example, is to frequently use large quantities of fly ash. Because those production units already exist; there is already a raw material stream and there is a factory that can mill it. There is actually nothing innovative about it — it is simply an existing stream that is already there, so you run that risk a bit less. Technical performance is not even such a big problem. We can get that sorted. We can get it defined at some point. Those kinds of things — we can make agreements with each other about them. Then I don't need any legislation or regulation at all. Even though the legislation and regulation is barely obstructive.

If you use a new waste stream, that problem does exist. You have to deal with tricky things like contamination values and so on. You don't want something to contaminate your material. Those are just boundary conditions you have to comply with. We are also working on that with various companies — to say: can you certify that, the certification of the boundary conditions for waste use. What you then look at is: do people accept it? Can you scale it up? Do you have enough of those waste raw materials that you can process into a binder? You could, for example, use the ash from waste incineration, but if we start incinerating less and less waste, I end up with less and less ash.

Sam: But that of course also applies to blast furnace slag and fly ash. Those are also raw material trajectories that may barely be available in the Netherlands in the future. Are there any specific regulations known in that regard for using those materials in geopolymer concrete? Or does something change in the regulation compared to regular concrete, or is it exactly the same?

T. van Beek: What you ultimately end up with technically — whether it resembles concrete somewhat — that is simply a matter of testing, tuning, and trying. Universities do a great deal of work on that. On the other hand, you need to have a consistent quality, and the market considers that more important. If you make something, it needs to be the same again the day after tomorrow — so that is an important aspect. Then you don't even have anything to do with regulators yet; it is simply a need from the market. You as an architect don't want spots in your wall — or do you?

I have experienced before being called in and told: there are far too many spots in it. Then the architect was called in, and he thought it was absolutely fantastic! Acceptance among each other, what kind of expectations we have, is one thing. And when you actually look at regulation, one of the things that can be tricky is that if it is waste, it has a waste status.

You can reuse it, but then it may not be called waste — because waste may not be used in construction. So first you say about the product that it must be circular. Then I say: my household waste is circularly deployable if I can use it as a raw material. So then I'm going to use it in construction again. But that's not allowed, because it's waste…. So something has to change there... I often hear from the market: How do I get rid of my waste status? And once I no longer have waste status, it suddenly becomes a raw material. And then I am no longer circular.

It is a definitional issue that needs to be carefully examined.

Sam: How does that work, for example, for construction rubble, which is now used as a base layer for roads? Is that also classified as waste or...?

T. van Beek: The trigger has already been pulled there: it is no longer waste, but it is a secondary material. We have indeed done this before, and in my view it is simply copy-paste — and you then need to do that for the other products as well. But what a government — not entirely without reason — is afraid of, is that people simply try to dump waste in this way. To some extent you can of course put whatever you want into concrete, or under the road — the layers that were put under the dykes no longer had waste status, so they were suddenly allowed to be used everywhere in one go. There were still some boundary conditions, but the contractors did not understand them, and the person selling it found it convenient too. So everyone thought: hey, that's a nice solution! But ultimately you end up with an environmental problem.

Sam: About that environmental problem — we also heard a great deal about it on the last day of the training week. They talked quite a lot about the tests — a kind of chemical tests that simulate an accelerated process — and that those are not necessarily suitable for geopolymers due to their different chemical composition.

T. van Beek: For environmental purposes, leaching is mainly what is looked at. And that is actually a fairly basic test. All you do: you put a piece of concrete in a device and force water through it under pressure. Then you look at what washes out with the water, and you measure that. It is called a diffusion test because you diffuse it through. It only turns out that with very dense materials, it takes a great deal of effort to get it through. That is a practical issue during the test. But then you can also grind it down again and test it just like a loose material. Then you also have a result. That is also covered in the regulation, so there are solutions for that. But the test is essentially just pressing water through the product. No substances other than water are used. That should simply work.

What you often hear from the technical side is: this test was specially made for regular concrete.

But that is not the case at all — it was not made for the concrete world, but for something entirely different. The test was actually made for soil and for sludge. It has nothing whatsoever to do with concrete. Complaining about test methods is a bit of a slipstream phenomenon.

In the same way, people occasionally even question whether simple compressive strength tests are suitable for geopolymer concrete. Well, in my laboratory I truly do an infinite number of compressive strength tests. And that is never the problem. I keep thinking: why is there yet again a need for a compressive strength test? Then the client says: the basic requirement is of course a compressive strength test.

Sam: What I had understood from that is that the compressive strength test is quite often carried out after 28 days, and that that was a bit of the sticking point for geopolymers?

T. van Beek: Yes, the biggest sticking point for geopolymer is mainly that, according to the standard — which is what we always do in practice, and what the standard also requires — you place the concrete cube in a water tank for 28 days and then test it after 28 days. The problem is that geopolymer concrete is particularly sensitive to water during those first 28 days. That is precisely when the hardening agent leaches out. But you are also allowed to use another method — in that case you place it in a room with high relative humidity, a mist chamber for example. That also works. Then it leaches out far less. And then it performs fine. Or you are allowed to seal it completely. I believe those are the three options. And then you also get different results — you see a certain difference. But even with regular concrete it has been demonstrated that if you keep it in the water tank for longer than 28 days, the strength also decreases. More comes out later — then the binder leaches out.

With geopolymers, that happens somewhat earlier. Yes. That is why the 28-day period is then not ideal. Or the water tank — then you do it the other way, and that works fine.

Sam: Are those kinds of parameter changes — because that is ultimately what you are doing, changing one parameter — is it the case that you can fine-tune those in the test so that your material comes out best? Or should you actually want the opposite? Because that is of course also something you often see — as you saw with car manufacturers, for example, who basically put a completely stripped-down car into the test just to achieve a certain value.

T. van Beek: You do need to test in the same way, and so you will need to take a step there. Otherwise you would have to do everything with a mist chamber. Many concrete laboratories would not be happy about that, because they don't have a mist chamber at all. Now, I can tell you that one is fairly simple to make. It is not a particularly special room. What you normally do is take a plastic container, put a layer of water in it, and place the cube in it. Or take that same container, lay a thin layer of water in it and a rack, place the cube on top of it, and close the container — then you have a mist chamber. So that should not be the problem. It is also a small matter of social impact.

Sam: Do you often see that it is not so much the material itself but because they are somehow afraid of things? Or is it more that they genuinely don't believe much in the technology yet, because it hasn't been proven?

T. van Beek: It very much depends on what type of application and where it is used. We also do a great deal in insulation materials, for example. Innovations pass through much more easily there — but your insulation material has to insulate; it doesn't collapse. Safety is considered much less important. But the problem you see there is that there are all kinds of chemicals in them. The most dangerous thing you can use is a bio-based insulation material. That is genuinely dangerous stuff — it moulds. If you have mould, there are toxic spores in your house, and in France people have died from it.

Sam: Oh seriously? This is something I have never heard before.

T. van Beek: We always think the Dutch are at the forefront, but France was actually further ahead in this area. So those materials were banned there for a while, until they found a solution. And that comes down to properly cleaning your bio-based materials. Then a chemical agent was used and they were no longer bio-based. They now have other agents for that. And now I see a great many bio-based materials in the laboratory, and you can see precisely which ones have been treated well and which haven't. If they haven't been treated properly, they are already rotting away in the laboratory before I get to test them. And in a sense, that of course applies somewhat to geopolymer as well. Because when you look at certifications such as an EPD or an LCA — yes, you are talking about raw materials that in principle, well, stone-like building materials can be fairly inert, but once you start activating them... what happens? Yes, then you are essentially working with chemicals. And you can also see that with the people working with them — they genuinely need to wear safety clothing. You go from a concrete factory to a chemical factory. The sodium hydroxide and those kinds of things arrive in containers with all those hazard symbols. So you have to adapt your safety arrangements to all of that. With cement and water it sounds fairly harmless, but I can also say that if you mix cement and water together — or cement in general — you should not touch it with your bare hands. No, although that is very often done in practice. I also come from the era when we simply ran our hands through the concrete. To check whether it was right. And back then you still had fairly clean cements, with few additives. There are increasingly more additives being added, and you don't always know chemically what exactly they are. They can also still be dangerous. And if you look at the official safety measures for regular cement and concrete, they are not much different from those for geopolymer concrete. It's just that with regular concrete we don't do that. We never have. And if I say "Geopolymer," we do. So from a safety point of view, with Geopolymer concrete in particular, I have a safe construction site — because you tell people again: this is new, I need to think about safety. With the other, we have actually never done that. If you look at Great Britain and see what measures they are required to take when simply pouring concrete — things we don't do — it is very different. A full face mask, for protection against splashing concrete getting in your eyes, or whatever. Your skin — you really shouldn't be pouring concrete while wearing shorts. The reason I sometimes think: yes, I simply cannot. Well, I find that no more than logical.

Sam: Coincidentally, in two weeks I also have a visit to Renewie's rubble sorting facility. So I'll be going there, and they also have a full safety policy. So you also have to walk around in safety clothing there. So it would be strange if, once you remove the product from that location, it suddenly no longer applies or something.

T. van Beek: Renewie is also clearly a waste processor — you deal with safety differently than at a concrete producer. The safety awareness at Renewie is a bit higher than at a concrete mixing plant.

Sam: Do you still see a difference there between concrete mixing plants that produce concrete on the construction site versus concrete mixing plants that make prefab elements?

T. van Beek: You often see the old culture there, so to speak. But if you look at most concrete mixing plants — precisely because you are also moving towards automation of the process — safety is also becoming an increasingly important point. You are much more focused on process optimisation. If you were to do that once, the word "safety" naturally comes around the corner. You then see that they include it, because safety is at that point a barrier in your process optimisation that can just go wrong. So that is increasingly being taken into account. Whereas a concrete mortar plant does things somewhat differently than a mixing installation — a truck comes along, I want some concrete, and they don't pay as much attention to it. It is a somewhat more primary product. It can be much more sophisticated. If you look at a modern prefab concrete plant — a top-notch facility — like Van Wijn in Heerenveen, you could practically eat off the floor. Walking through there, you have absolutely no sense that concrete is being produced. Walls are simply being produced. Everything is clean and neat and safe. They also had a concrete mixing plant right next to the factory — that was convenient, no need for a separate one. But despite having that concrete mixing plant, they nevertheless built a new one, because that concrete mixing plant was not precise enough. They are also, by the way, looking at whether they could deploy geopolymer concrete, and they say they are still dealing with that consistency issue... You need to have a very consistent process, and what is being delivered now is not yet consistent enough for them.

Sam: Yes, because I think that is mainly also related to regulation — like your EPD, if it is not described as consistent.

T. van Beek: Well, for the EPD it is not so bad. That is my calculation. And if your inputs are reasonably in order, everyone is happier that the calculation comes out somewhat. That is not really the issue — it is more: do you have the data? It took a very long time before the EPD for sodium hydroxide was known — then you have no input, you can't do the calculation. Yes, that is understandable, because it is only a handful of factories that make it, and if they don't feel like delivering it, they don't deliver it. They are not obliged to deliver it.

Sam: Are there still very large steps to be taken in that regard — not about an EPD, but about real European standards or codes, design codes, etc., for architects, for the market, etc.?

T. van Beek: I have been sitting regularly with concrete structural engineers myself lately. What do you actually need to be able to calculate a structure? You know, if they know certain performance characteristics of the material, they can essentially do the calculation. If it resembles concrete sufficiently, the calculation works out. It is more a question of: where, when does it work? And occasionally we also had that discussion: a 10% deviation in the modulus of elasticity is not serious — it is already there with regular concrete. 20%? 30%? Yes, then it becomes serious. Where exactly is that boundary? When do you accept a deviation and when don't you? So that also needs to be agreed upon collectively. If they have that data, they can do the calculation. Rather than people saying it deviates strongly. You can also just do a test on a wall. Test that wall to failure, see what it does. If it does what your calculation says, it's good. If it doesn't do what your calculation says, you have a problem. Then you can come up with something else, but you have a result. Maybe you need to develop a new calculation. Well, I think there is a very large difference in thinking there compared to what I see happening in the lab and what reality actually does. In the lab they essentially do a compressive strength test and then say: hey, this many megapascals came out. And that is put into a calculation model, and from that model all kinds of things are derived. And you see that that doesn't work for geopolymers for various reasons. But it is not very difficult to then also do a test that checks the other values as well. Not only relying on what the model says. Then you see that the model doesn't match reality, and either the calculation or the model needs to change for that material.

We are also working on that in the Netherlands, and internationally too — you can also see it in the international pre-standards, as I would call them, that we are developing — where we say: yes, we are going to deliver concrete on the basis of performance and we are just going to measure it. And we are going to do that measurement either in a certain way, or if I simply measure an entire wall in one go, then I don't need to measure the concrete at all — I don't even need to know the compressive strength; I know the strength of the wall, and I'm done. And that is also called "design assisted by testing." In principle, what is simply laid down in the standard, even at European level. But when I ask structural engineers or designers: have you heard of it? Yes, they have seen it mentioned in that appendix, but applying it? They've never done that. So we are now trying to nudge things a little in that direction. Along the lines of: take a look at it, because it's not that complicated. No, they say — I want to see the statistics. But that is just a fill-in form — you do it yourself in Excel. We use it for other products: applying stone strips to insulation material, for example. We do that according to the same principle. That is fully covered in terms of standardisation. Under the European standard we only ever encounter one remaining boundary, and that is when at some point it is also assessed by the government — is this good enough? There is a great deal of variation there; if it is not good, then that must also not be good... That is sometimes where the brake is applied by the government. We do not accept it because it is not according to the standard. Yes, it is according to the standard — I have simply done everything I needed to do.

Yes, but it is not Eurocode 2 — no, it has been scaled up to a higher level. That is the base. We have used the base instead of a derivative of it. But that is something we normally never do, so we don't accept it. We have had bad experiences with testing by the government — they do one test and then we just have to accept it. Then you haven't read the standard properly — it states that you need to carry out a minimum of three tests. That is knowledge, so to speak. If the knowledge is also present on the other side, trust will follow. And you notice that — because we have also touched somewhat on the trajectories that you as a potential producer of building elements can follow. You then notice that for geopolymers specifically, there is more of a trend to approach it in the way where they first make something that works — something they are confident in. As Sqape has done, for example — they simply have one recipe that they know works, that is qualitatively and quantitatively in good order, and from that they make something that is going to be tested, rather than trying to pick up the fundamentals of the material and essentially trying to tackle a much bigger problem that is not necessarily needed for their product. Yes, in the beginning I gave a great many lectures on how you can approach this. Keep it simply stupid — that is a good start. You begin with, for example, a paving slab. In paving: if it breaks, or as I once had with a province that said — well, I want to make a cycle path out of it; if it goes wrong, you have a nice gravel path. So: choose a low-risk product. And on the other hand: don't immediately start talking to Rijkswaterstaat, I always say. They want to have seen everything first. You can make the biggest bridge that exists in the Netherlands for them, but then it has to comply with all requirements. You are in a development phase — learn how to handle your products, learn to build confidence, try to achieve that continuity, because companies like Sqape also really struggled with that in the beginning. Always that continuity — Sqape's product is now entirely consistent; you see almost no variation in it. It is perhaps even more stable than cement, because they have to do better than cement. So sometimes, when everyone follows the rules properly, it is more precise than regular concrete. But when it suddenly fluctuates a lot — when I see an outlier — I have to ask: what happened? I had a different mixing master... who had never made that before, and he had to make a different product, and that's often where it goes wrong. Trucks that aren't cleaned properly, for example — that kind of thing — contamination getting in. Yes, regular concrete ends up mixed in with the geopolymer concrete. Yes, then you get a completely different product. But is that a very big problem? I hear that very often from people in the concrete industry — they are very concerned, also for lifecycles, that these two products essentially cannot be mixed together. Both at the raw material stage and in hardened material. If we look, for example, at reusing construction rubble as aggregate, then regular concrete enters geopolymer concrete, and it is not inconceivable that the reverse also happens. It already happens, of course, that construction rubble is used as aggregate for regular concrete — in some instances that can then lead to cross-mixing.

Sam: Is that something that in your view needs to be strictly kept separate?

T. van Beek: No, I think that is a dead end if that is what you want. The rubble we receive now is from buildings 50, 60 years old. No idea what that concrete looked like at the time. We crush it and we assess the performance of the grain we get. If it is good, we put it back into concrete. That can also be a chemical aspect — is there something in it that is not good? You test that: Does it have an effect? All those tests are available. Does it have an effect on the new concrete I want to make? Then I can't use it. And essentially, after 40, 50 years, that material is completely inert — just like regular concrete. If you break it again, and you break it properly, you ultimately retain the aggregate particles; you retain sand and a fine fraction. You actually need to assess all of those fractions: is it good? The gravel, the sand — you need to check: is it good? And when you then look at that fine fraction, what sometimes comes out of that is that the contamination sits in there. Then you can no longer use it.

Sam: So the problem mainly sits in that fine fraction, really?

T. van Beek: Yes — or can you convert it again into a filler or a binder? Then you could prevent the problem. Then you are talking about converting the smallest component. But you can at least reuse 75% straightforwardly — the last 25%, that still needs to be looked at.

In the Netherlands we also have a somewhat significant challenge with masonry brick walls. You often see there as well that the problem is the fine fraction when you crush it — because it contains both the mortar and the brick. And you don't really want that. And then I come to a brick factory and I see that they mix clay with fine material to change the properties — so that the fine fraction is actually added there. It is different from what you are used to — it is naturally much easier when you have a primary clay and a primary sand; then it is much easier to steer. But with residual streams: there you have a material stream of which you don't know exactly what the properties are, so you need to make many more adjustments to still get a good end product, and perhaps also test much more. It costs enough money.

Sam: Do you believe that for the reuse of these kinds of materials you actually need to be much stricter? Or would you say: actually you need to give them a bit of room, because we are working on something good to close the life cycle.

T. van Beek: What I actually see now is that the requirements for these kinds of innovative products are always higher than for the regular products. And yes, that makes it very difficult to get something to market. And it is not so much the requirements from regulation, but more the need to gain trust. Banks only have that trust once they have added their own extra requirements on top. Asking: what else is actually still needed? Saying: I still want to know that, I still want to know that. When you think you have investigated everything for a client and can no longer think of anything — for the next client it is still very easy to think of something new. Everything that already exists, okay — you list it, you tick it off. But will you go and think up something new again, and purely just to gain trust? Yes, you will then have to find a middle ground: what do you actually really need?

When I saw what requirements were being set at some point for a paving stone — why do you want to know all of that? The only thing I normally want to know about a paving stone is not even the compressive strength — I just want to know the flexural strength, because the stone breaks under bending. I can't do anything with the compression... But now they do really want to know that, because it is new. If I make it from something completely different and I don't call it concrete, you don't need to know... So you have to engage in that conversation with each other. Then you arrive at a shared requirement. That is ultimately the idea. It is of course a bit of a "what if," but those are the implications for architects really.

Sam: So how should you as an architect deal with this in order to manage it? And I think that connects very well with what John Provis said during his talk: "Find the right solution for the right place for the right problem." There you see that you could deploy this material for 20,000 different building elements. And I think it then becomes more of an engineering question of: where are you going to apply it and how are you going to use it? Rather than trying to make some kind of exact copy of concrete. You are better off knowing what performance actually comes out of it and where you can deploy that performance.

T. van Beek: Yes. But this is simply the performance it has. And yes, it may deviate from concrete. Maybe it's better? We recently came across one of those as well — yet another type of concrete — and it had a much higher flexural and tensile strength. It was actually better, therefore. But we always put reinforcement in for that anyway, so we don't need that increased flexural and compressive strength... But then you can leave the reinforcement out. That is a CO_2 emissions difference.

Sam: Was that geopolymer concrete?

T. van Beek: Not geopolymer — that was a sulphated cement. There even seemed to be a standard for it. And still it is not used. Yes, that is again rather remarkable. The regulation is completely in order, and it still isn't used. But I also once saw the price tag. It is often compared with regular concrete. Regular concrete costs 150 euros per cubic metre, that material costs 300 euros per cubic metre. Yes, then it is twice as expensive and they think we can't use it. But the fact that you no longer need to put reinforcement in it — in reality that may save you much more. The total cost of ownership is not examined. I have had that discussion too, because you see a great deal of research into concrete mixes that contain some kind of fibre reinforcement. But when you work through the economics of that, it is actually nearly always barely financially viable, because the fibres are so enormously expensive. You need to put in just as many kilograms of steel as with conventional reinforcement. Conventional reinforcement doesn't cost that much — it is practically the scrap of the steel industry. That normally goes into concrete. With fibres it is a much higher-grade steel, and that also has many other applications. In your car tyres, for example, there are also fibres. And then they can earn much more from it than by putting it into concrete.

Sam: On top of that, you of course also have the people in the concrete industry who have a kind of monopoly. I spoke to people from CRH and they said they are currently essentially the supplier of steel slag and fly ash for geopolymer concrete. Then you can of course set the price as high as you like. They do say: yes, but we use it as additives in regular concrete, so it is a high-value material. But they determine precisely where it goes and to which laboratories across Europe it can go at all. That is why they essentially control to some extent what the price is when you use it for something innovative — and that has nothing to do with the price you would normally have if you were using it as an additive in concrete. They are such large players that I think those comparisons are quite difficult to make.

T. van Beek: Yes, you don't really have a competitive market then when it comes to raw materials. It is also a bit of a brake on innovation — that they have too few competitors. And their product is also not accepted, because people can only source from one supplier. And a buyer doesn't want that. You don't want to be dependent on just that one. There needs to be a playing field. And I then think: in my view you also need to tender far more on environmental performance. I want a low MPI, or whatever, low CO_2. And then you'll also get there with your solutions.

Sam: Is that, do you think, a future we are heading towards? That there genuinely needs to be active compensation for CO_2?

T. van Beek: Economically speaking or in market terms? The municipality of Dongen at some point constructed two small bridges, and in the tender they did not specify that geopolymer was needed. They did say that innovative products outside the regulatory framework would be accepted provided a certain level of oversight was in place. But they essentially said: yes, in tendering the environmental impact is simply weighted very heavily. And at that point it became geopolymer concrete. They had not prescribed it — they had not said: innovations such as geopolymers will be included; no, just innovations in general. If someone had come with something completely different and had been able to demonstrate it was good, it might have been that. They had arranged it so that for innovations, additional funding was available for the supplementary costs of research and such things. So the more expensive material: that was the contractor's cost — so it wasn't tendered separately. He therefore simply had to price it competitively against the environmental performance. There were three bids — two were very close to each other and both had used the same Sqape mix. One hadn't gone to Sqape — had done a regular concrete mix — so he also lost, because his environmental costs were so much higher that he still lost. Even though his construction costs were reasonable. Concrete is only a very small part of the total construction costs. So the concrete was indeed twice as expensive, but then the whole job only became 10% more expensive. If you then achieve more than 20% reduction in your environmental costs on your effective bid, you win.

Sam: That brings us back to what I keep saying: use it for the qualities it has. If, for example, as an architect you want exposed concrete, for instance — yes, then you get fire safety problems and who knows what else. But if extreme fire resistance is a quality of the material, then you can start using it for that. Then it is a matter of deploying the material in the right place.

T. van Beek: That is essentially a bit the brief of the designer, yes. That is: what do you expect from a material — appearance, strength, fire resistance, etc.? Even though I think we don't quickly have a problem with concrete and fire resistance. It is naturally fairly fire-resistant in itself. So I don't really see the added value of geopolymer concrete there. But an example of other alternatives: there was one in Belgium that had the real problem that if it got above a certain temperature, the concrete simply melted. Then you simply know: I must not use that for a house. Okay — but it did have a much longer service life, of around 200 years. So it is now being used for railway sleepers. It is suited to that third context. Because it also turned out to be very resistant to stray currents. They discovered that by trying it themselves. It had a very high electrical resistance. Much better than the usual variant. That was something they hadn't thought of beforehand. I do think that is where the strength lies. And that research also needs to go in that direction.

Sam: I actually found it quite shocking to see that I was sitting at the symposium as the only "Architect," so to speak. And everyone also said: but why are you even interested in this material? And I actually found that already a rather remarkable question. Because I think that precisely from my side of the story, the demand is primarily generated.

T. van Beek: I was recently also working on a concrete course for architects — to get a bit of knowledge across to them. And mainly because the architect decides. He naturally determines the choice of materials. So you do need to know what you are choosing. And also according to the principle: unfamiliarity breeds indifference. So you need to sit down with a few architects. What knowledge do you actually need to make that choice well? What is important to you? And when I then put a group of concrete technologists opposite them, they look at it in a completely different way. That is also the case at that congress. You then mainly see the technological input. You think genuinely: starting from the molecule, we're going to see if we can make concrete. You look from the angle: I want to put up a building. It needs to look good. It needs to function well. And then you ask yourself: what kinds of materials could I use for that? You take the approach from a completely different angle. And somewhere in between sits the structural engineer — who also looks at it differently. He needs performance. Which materials are used — he doesn't really care. Whether it's geopolymer concrete or regular concrete makes no difference to him. That is an interesting discussion.

Sam: You do indeed, if you look at people in the lab and so on, have a different angle. They are essentially looking from microstructure right through to a structure, and that is also a framework. They also show that. But the line stops there. But when I look at my field, you have a structure and it is implemented at a location. And the location has all kinds of boundary conditions, and it also has to fit within the social image and goodness knows what else. Those are much larger things than essentially a bridge — and I also think that is somewhat the strength of people in my field. It is thinking across scales and essentially trying to find a somewhat holistic approach to a specific problem, and making that puzzle.

T. van Beek: I was recently in a discussion about the appearance of a neighbourhood, and there had to be bricks according to the architect. I said: well, you can't prescribe bricks. I said: you can prescribe the appearance of bricks. And then you leave the choice of how to achieve that to the other parties. But isn't that the same as prescribing bricks? No, because nowadays we simply make thin stone slips — very thin — and they look like bricks. For the architect, that would essentially make no difference. A few architects say: that's fine by us. But others say: you can't recess the joint as beautifully; that shadow effect. Then the designer of the stone slip gets back to work, making one with a nicely recessed joint. And that does come along, you know. And in terms of appearance it simply is brick — but it weighs only a tenth of a normal brick. Yes, ten percent, indeed. I do think that kind of ingenuity is always possible but often not chosen. But it all stems from a kind of — perhaps a lack of knowledge among the various players. And that communication is simply poor.

Sam: I definitely notice that myself — because I also stand on the construction floor as a contractor. And I notice that being able to communicate already solves a great deal.

T. van Beek: I think attention to certification and such things plays a large part in that. It is a large part of the fear we were talking about. What a certificate often does is remove that fear. Because if it complies, a great deal of the communication we were talking about is no longer necessary. You don't want to have to do that again every time. So you try to summarise it in a certificate. We've already discussed this once — we are not going to do that again for every construction project. And that is a bit what you currently see with geopolymer concrete. Every time you have to go through that whole discussion again for projects it has already been done for. I then get called in, from that certification role, to somewhat break through that discussion. Well, we'll sort that out — then we have confidence in it. It simply saves a great deal of discussion, then you can move forward again. And if it is then also captured in a standard, that discussion becomes even easier.

Sam: Because I also know that you said at some point that in principle you just look at what the difference is compared to the other. But where it is the same, it is essentially the same. So you don't need to redo it. Do you notice that if you do that often enough, you have in effect organically obtained a kind of standard?

T. van Beek: Yes, you do see that more and more often. We also occasionally produce what we call assessment guidelines — a kind of standard-like documents. When you say: we have seen this often enough — we'll just write it down once. Does everyone agree? Yes. Okay; it is not yet in the standard, but we are now collectively in agreement: we're going to do it this way, otherwise we'll keep getting stuck in that discussion every time. Then you can make progress again.

We have, for example, discussed the use of recycled aggregates in concrete. Up to a certain percentage it is allowed — then it is not a problem at all. Above that, it is not permitted according to the rules. Everyone wants to go higher, but it is due to the standard that we don't use a higher percentage. Then we issue a recommendation in which you demonstrate when it can be done, and under what conditions. Well, if you meet those conditions, it is fine. It is always somewhat difficult though — because someone simply picks up the standard norm and says: yes, but I'm only allowed such-and-such a percentage — 30%, but I'm doing much more: 50%. Yes, that can't be done according to the standard. But I have demonstrated that it can. That is then still okay, provided everything is certified. We then try to push that through. But that takes a long time. Those are processes that can take 5 years sometimes.

Sam: What needs to be done to implement this material on a larger scale? And what actually needs to change in order to really use it as a building material, as we now use other building materials?

T. van Beek: Yes, from my perspective I simply say: you need to make sure the regulation gets sorted, because technically it is all well put together. I am no longer as technically worried. When I started with this, ten years ago, I said: you need a solid technical underpinning. That already exists now. There are now also working groups busy simply writing that standardisation. In Belgium they are already quite far along. They have looked carefully at how we do things in the Netherlands, and they are simply writing it down. I always find that admirable about them — they are somewhat more progressive in that regard. If something has been proven, it has been proven. Before that, they are very sceptical, but once they push through, they overtake us.

It is also always about large quantities. So you need investors who dare to believe in it and dare to invest in it. And you should also not expect that if you invest now it will be on the market within two years. The iPhone started development ten years ago. That is the latest state of the art from ten years ago. That simply takes time. We also need to accept that. It simply takes time, patience, and money. And it is not the money from just opening a subsidy pot — because building a factory is at minimum 20 million euros.

Sam: Do you think that we as architects have a role in that? In nominating those innovative materials rather than essentially continuing to play with what we already know?

T. van Beek: Yes, the architect certainly has a very important role in that. He needs to put up a beautiful building, but it also needs to be a functional building, and nowadays simply a sustainable one too. I often see that things are always started very optimistically at the beginning, but ultimately a great many things get written out. But that is always the case, also with technical things. At the start everyone always talks about that fantastic palace, and ultimately no magical palace materialises but a semi-detached house. That is simply how that process goes. And that also applies to requirements relating to sustainability. But I do see how much patience some architects have had.

I don't think the gap between geopolymer and regular concrete will take that long to bridge. The difference is not that great, because they are both a kind of stone-like building material. So the differences are not that large. The colour may differ somewhat, but as an architect that is also interesting.

An example was a geopolymer building. It was a very sustainable building, but no one was satisfied — because it didn't look sustainable. It just looked like new-build concrete. A recent example in Amersfoort: they happened to put up a very beautiful residential block in timber. One is simply made from calcium silicate stone and the other from timber, but you can't see the differences between the two. Then everyone goes around grumbling: which is the sustainable building of the two? You can't tell. That is indeed something. But yes, it is then perhaps also up to the architect to somehow show that in a certain way. In another location there is a building in timber where you can clearly see it. Everyone says: that is a sustainable building. While I know from the figures that it is less sustainable than the other building, where you couldn't see it.

That is something you as an architect need to think about in the development of technology and such things. That people judge a great deal by how something looks on the outside.

Translation by Claude 4.6 Sonnet — original interview conducted in Dutch.

Interview 2: Maiko van Leeuwen (concrete technology)
[Full transcript - Dutch original. English translation: see below.]

Interview Transcript 2 – Maiko van Leeuwen

Maiko van Leeuwen – 00:00 My name is Maiko van Leeuwen. I worked for 27 years at a concrete mixing plant as Head of Quality Assurance and Concrete Technologist. There I was responsible for managing the mix designs and production control. About 12 years ago I moved to TU Delft, where I supervise bachelor's students, master's students, and PhD candidates in their research into cement-bound materials, as they officially call it. The great advantage is, of course, that I bring a wealth of experience with me. I have produced approximately 1.3 million cubic metres of concrete in my life. And then you can supplement the academic knowledge that is abundantly available here with my experience. And that is genuinely very valuable, because we can come up with the most wonderful ideas, but they also have to be practically feasible and verifiable. And the advantage of my age — when you are as old as I am — is that you know a lot of people. So my network is now quite extensive. It is therefore also fairly easy for us, when we want to test something in practice, to approach someone so that we can actually go and do that.

On geopolymer concrete: very simply — concrete is in transition. The way I learned as a young person of your age to make it with sand, gravel, cement, and water — we no longer want that, for various reasons. Most are environmental in nature, and that means we want to make concrete without cement, for example. And that is where geopolymer concrete comes in — where you don't use cement as a binder, but a by-product of the steel industry. And that is slag. The reaction is considerably different from that of cement and water, I must say, but with just a little bit of imagination you can call it concrete — because you have a binder and that binder glues the aggregate materials together, and that is the similarity with regular concrete.

Sam Meeuwis – 02:30 You actually immediately started talking about the difference between Portland cement-bound concrete and geopolymer concrete. You also immediately said that geopolymer concrete is essentially always bound with slag. But it is precisely interesting as an architect to look at the potential of a material — how it looks, what its properties are, etc. Especially with geopolymers, because such a wide range of ingredients can be used, a fascination arose for me. Because it is actually much more broadly applicable, perhaps, than regular Portland cement concrete. And within my research I am looking at the potential of geopolymer exclusively in the Netherlands. So we are also looking purely at the raw materials available and the raw material streams that are present in the Netherlands. In that context, blast furnace slag and fly ash will probably not really be usable. Of course, there are many different factors that can influence that. But if we look at the biggest difference between geopolymers and Portland cement, it is that geopolymers can be composed from many more different raw materials than Portland cement. And you can also blend those raw materials. What is then the most important thing to think about, bearing in mind what influence that has on workability, in your opinion?

Maiko van Leeuwen – 04:30 Well, first of all, geopolymer concrete actually has the same possibilities as regular concrete. By the way, you keep saying Portland cement concrete — but 80% of concrete production in the Netherlands is not made with Portland cement, but with blast furnace cement. That means the blast furnace slag is already in it, supplemented with Portland clinker — I have to admit that, that is true. But the majority of concrete production in the Netherlands is made with a blast furnace cement, a CEM3B — and a Portland cement is a CEM1. Other countries around us use mainly Portland cement, that is certainly correct. Yes, you know — that availability of materials for geopolymer concrete? You have exactly the same problem with regular concrete. Naturally — because sand and gravel will no longer be allowed to be extracted from the rivers in the near future. Those concessions are simply no longer being issued, so you essentially have the same problem as with blast furnace slag. The availability of blast furnace slag is naturally dependent on how steel production in the Netherlands is running. But you already have a bit of an idea of which direction that could go. But I don't have a crystal ball — I cannot look into the future. If it were not available, you would have to import it, and that is of course considerably more expensive, for a start. But that is in principle not the architect's problem. We simply have to get on with that transition whether we like it or not. We have to change, because — as I said — sand and gravel can no longer be extracted in the near future. And yes, public opinion also essentially doesn't want cement anymore — doesn't want regular cement anymore. That is actually almost not done, and that is partly unjustified. Because the cement industry has a somewhat bad image, because they do of course have quite significant CO_2 emissions. On the other hand: if there is an industry sector that does everything to make its production processes more sustainable, it is the cement industry. And they don't always get all the credit for that. That is indeed a great pity. The CO_2 emissions from blast furnace cement, which we make, are by the way much lower than those of Portland cement, so in that respect we are already making very significant savings in the Netherlands. But of course it can always be better — I immediately agree with everyone on that. But how that will go in the future, I don't know.

In terms of performance: in 9 out of 10 properties, geopolymer concrete is equal to or better than regular concrete. There is one major disadvantage — or one major challenge, as I prefer to call it — and that is maintaining workability. That decreases very quickly with geopolymer concrete, because there is no gypsum in geopolymer concrete. In blast furnace cement — CEM3B — there is a very small amount of gypsum to regulate the setting time. It retards the setting slightly, so that it doesn't harden in the truck mixer.

To put it very, very bluntly: the code states that concrete must remain in the same workability for at least 1.5 hours, because you have to make the concrete, then it needs to go into a truck mixer, that truck mixer has to drive to the construction site, and it has to be poured. That takes time, so in Europe we have said: it must remain in the same consistency class for 1.5 hours.

With geopolymer concrete — especially the versions where you only use slag and no additions such as fly ash — you don't achieve those 1.5 hours; you're looking at 20 to 25 minutes. Well, by then the truck mixer has barely set off, so you have a problem. So what you currently see is that in practice, geopolymer concrete is mainly used in the prefab industry, because then you don't have that problem with travel times. So you have a factory, you fill the moulds with the geopolymer concrete right there and let it cure before you transport it. In the future you will see that it can also be done for in-situ concrete. But it is simply still the case that work needs to be done to improve that workability. You can work with retarders — there are retarding admixtures. I always say the best retarder there is, is water. But with geopolymer you basically can't use that, or at least only very limitedly, so you also have to take that into account. But otherwise I see no real obstacle to continuing with geopolymer concrete. The only property that is somewhat more extreme than regular concrete is shrinkage. That is an issue, because as a structural engineer you do have to take into account that the shrinkage is considerably higher than in regular concrete. You can't have a situation where you pour a 10-metre beam and a year later it turns out to be 20 cm short — then we have a problem.

Sam Meeuwis – 09:30 My opinion — also after attending the course — is that geopolymer concrete is indeed extremely useful for the prefab industry, but not yet for the in-situ situation. Do you think that is necessarily a disadvantage? Because precisely in a prefab situation you can determine all those curing conditions and how it is formed far more precisely.

In a prefab setting you can create the conditions to meet those requirements, or at least to get the best qualities out of it, because you can simply create rooms with specific conditions. You can set up the factory in such a way that all those elements come out at the highest possible quality. Do you think that if you were to set up a factory in that way, you would still encounter problems that you would normally encounter?

Maiko van Leeuwen – 11:00 Well, first of all, every concrete factory that is going to make geopolymer concrete will have to convert its entire factory — if only because of safety regulations. Look — geopolymer concrete is simply even more alkaline than regular concrete, so you genuinely have to take that seriously into account. I once experienced a case: there was a test project with geopolymer concrete, and one of my colleagues was leaning against a container with activator — but that container was leaking. So his entire back was wet, and when we told him: hey, you need to take your clothes off and change, because that's not good — the man said: oh, I'll do that once we're done. Wrong decision — because that man simply had third-degree burns on his back. Just to illustrate that you have to deal with that very seriously. But that applies to concrete in prefab as well — they have to take the same precautions; the only difference is that the problem comes later. The problem actually only starts once you start transporting. Processing in the prefab factory is easier, because — as you say — you can simply create the conditions that are optimal: temperature, humidity, covering, whatever. None of that is a problem.

On the construction site, the first problem you will need to tackle is maintaining that workability — because you do have to drive an average of 25 minutes to a construction site, and you need about half an hour to pour a beam, or even longer for a floor slab. But all of that can be sorted, I think, with good retarders. The prefab industry simply has the great advantage that you have no travel times. That's the whole story. But converting that factory is exactly the same for both prefab and for an in-situ concrete mixing plant. In the Netherlands there are a few major players in the market who produce and transport concrete and who are always jostling for position as to who is the biggest. They work in clusters — they have regions — so you will see that they are not going to convert all those concrete plants to geopolymer concrete, certainly not in the first 10–15 years. No — per cluster, per region, they will convert one factory to geopolymer concrete, because you can't go from 100% regular concrete to 100% geopolymer concrete overnight. That will take a period of time. And that is partly for cost reasons. Because I think converting those factories will also add up quite considerably — but you will see that the largest producers, certainly the top 3, will fully equip one plant per region for geopolymer concrete, if they haven't already done so. At Mebin, I know they have already done that for geopolymer concrete.

Sam Meeuwis – 14:30 Okay, so that transition is actually already underway in the Netherlands?

Maiko van Leeuwen – 14:30 Yes, absolutely. Look — the concrete industry is not going to wait for TU Delft. Until all those studies are finished, or TU Eindhoven, or whatever. They are themselves also working on all kinds of projects. They are also engaged in all kinds of research. An example: Mebin is owned by C-ensie — that is one big cement factory, as you know — which is in turn owned by Heidelberger Materials, etc. Those are enormous companies. They are already fully engaged with this. They already have pilot projects. They have their own research centres — only they very often want to verify their results against those of the university, to verify what they have tested, whether it truly checks out. And universities of technology have quite a good reputation. That is why they like to benchmark their results against ours. But it is not the case that they say: well, you all go ahead with all that research and we'll just quietly wait until the results are known. There is simply no time for that. Because clients are already asking for geopolymer concrete — make no mistake. That is actually already happening now. You need to understand properly: with new products in the concrete industry, there is always a certain reluctance to start using them, because they are often just a little more expensive than regular concrete. Perhaps typically Dutch, but the cost comes before the benefit — so what you see with these products is that they are first made mandatory through tendering for projects by central government, Rijkswaterstaat for example. So then you may only tender if you are also going to deliver that concrete as geopolymer concrete. Otherwise you can't even tender. And once that becomes established practice, you will see that the price also automatically drops somewhat. It will move a little towards the level of regular concrete, and then the general public will also start using it — that's how it works. We've seen that with recycled material: with concrete it started sparingly with Rijkswaterstaat projects. And now it is actually entirely normal to replace 20% of your coarse aggregate with concrete granulate — and your generation is essentially going to use only recycled concrete granulate, no more regular gravel.

Sam Meeuwis – 17:00 Yes, that immediately raises the follow-up question. Because I come from the architecture side, it is also a question for us of: how do we close the lifecycle of buildings? What you see now is that buildings are mainly made with, for example, bricks that are mortared together. Those cannot be taken apart — they get pulverised and are literally used as filler material under roads. About 95% of BSA goes there, I have heard. At some point we are going to run out of new roads to build... It is also not high-value reuse.

Maiko van Leeuwen – 18:00 Well, you have to distinguish between concrete granulate and masonry granulate — those are two different entities. Masonry granulate is indeed mainly used for embankments, railway ballast, and that sort of nonsense. Concrete granulate — we used to call it concrete rubble, which actually sounds rather unpleasant: like, it's essentially junk and we need to do something with it, so just throw it into concrete. But if you look at the quality of concrete granulate and masonry granulate, you see that that quality has improved enormously over the last 10–15 years. So even masonry granulate can be mixed with concrete granulate and used as aggregate material in concrete. If you know a few parameters of those materials. You can actually put almost anything you want into concrete — almost anything — as long as you know certain parameters. Then you're talking about sieve analyses, absorption, adhesion, bulk density, etc. If you know those parameters, you can put virtually anything into concrete. That is the beauty of concrete as a building material.

Sam Meeuwis – 19:00 That is actually also part of my research. What I want to investigate: can we really use all those different rubble and waste streams to make things as circular as possible and to maximise the impact? For that I am going to Renewi's rubble recycling facility in Amsterdam tomorrow, by the way. I'll be going there to see how it actually works and how easily the separation happens. How much comes in, what are the volumes going out, and is there even a need right now to direct that towards construction rather than other destinations?

Maiko van Leeuwen – 19:30 Well, that need certainly exists, and I think tomorrow the scales will fall from your eyes — because what you are going to see is genuinely very interesting. They will probably tell even more glowing stories, because it's their own shop, than I already do, but I am truly very positive about it. When I started 25–30 years ago, we already had recycled concrete granulate. But when I walked over a pile back then, I would have two buckets full of wood and plastic pieces and bits of iron in no time. None of that anymore — it has become so much cleaner. You really have to search very hard to find a piece of wood or a piece of plastic. So there is a world of difference in quality by now, and certainly now — because I believe Renewi also has access to smart crushers. Yes, those can make almost any grain size and shape they want, and they can go so far in washing and separating. That is astonishing — it is genuinely very impressive.

Sam Meeuwis – 20:30 That washing is important for adhesion. Do you foresee problems in the use of certain streams of construction rubble — since it is now being separated — that geopolymer will shortly come back and be recycled and used as granulate for some building materials, such that you'd say: that really does need to be removed from the concrete. Including, for example, gypsum.

Maiko van Leeuwen – 21:30 Yes, it depends a bit on the application you're going to use it for. Are you going to pour a floor that needs to be power-floated smooth? I'll give an example: a floor in a DIY store, a factory floor — it has to be mirror-smooth, completely level. If you have things like wood scraps or gypsum in your material and you compact it, they float to the surface and you end up with all sorts of pits in your floor. And that's already not nice. It gives a kind of pockmarked appearance, which is unpleasant, and it is easier then — because of all those pits — for harmful substances to penetrate. So they don't want that, for example, in a floor for a petrol station either. Because then, well, you're already done for at that point — so you have to take that into account. But if you are talking about foundations? About certain columns? Then you don't have that problem. What you are increasingly moving towards is customisation. The client wants a tailored solution. It's not a case of: just bring some concrete and we'll throw it somewhere. No — you look at what you are going to pour, you look at how long it needs to last. From an aesthetic point of view, we are increasingly demanding. So you are increasingly moving towards a situation where, as a concrete technologist, you go into discussion or conversation with your client, with the contractor, and you genuinely find a solution.

Sam Meeuwis – 23:00 That is indeed how I see it — as was quite clearly described during the symposium during the training week: "it must be the right solution for the right problem in the right place." All those things have to line up, and precisely the variety of possibilities you have with geopolymer concrete is then interesting. That is what suddenly gives you a whole range of options.

Maiko van Leeuwen – 23:30 That is why it is so important that right now a great deal of attention is being paid to education and informing architects, structural engineers, and people who write specifications — because they at least also need to know the basic knowledge of these kinds of materials. And of course they don't need to know all the finer details — that's what people like me are for — but you do need to know a little bit about what you are talking about. Otherwise, as a concrete technologist, I'll read a specification and see the most astonishing things go by. That has honestly been a problem since I started — often too little attention is paid to it. Because a great many structural engineers do, for example, have the concrete technologist qualification on paper, but they don't practise it — they don't do anything with it. And then you'll just look in a book to see what environmental class you need and which water-cement ratio goes with it, whereas that is sometimes not necessary at all. We have a great many problems in the Netherlands with car parks, for example. Car parks have to have a very low water-cement ratio, and then a structural engineer assigns a strength class of C25 to that. That means it has to have 25 MPa after 28 days — but with a water-cement ratio corresponding to those environmental classes, it is C45. With that water-cement ratio you arrive at a strength of at least 45 MPa. That is 2–3 strength classes higher. That makes quite a difference, because for example the amount of steel was not calculated for that. It was calculated for C25, not for C45. If you go shopping with your partner at the weekend and park your car in the car park at the edge of the ramp and the floor — please have a look. I'll bet you ten euros right now that there are cracks there. And that is simply because the strength class does not match the environmental class. You need to know that. In Belgium you are not allowed to pour car parks in strength class C25. You have to use at least C37. Because they do understand that. And you are going to get the same thing with geopolymers. You simply need to know a little bit about what you are talking about, and you need to look at each application for what you are going to use it for. Do you have additional aesthetic requirements? There is a quality recommendation for that —

in my view the KEUR 100 — which you can partially apply. But you will also need to adapt it somewhat to geopolymer concrete. So behind the scenes there is quite a lot of work going on to get all of that sorted. All concrete types in the Netherlands are certified. That is very important. So it is also important that that happens for geopolymer concrete too, because otherwise as a contractor you can't even use it. They are already working hard on that — but it still needs a bit more time.

Sam Meeuwis – 27:00 What do you think still needs to change in the Netherlands to really get geopolymer concrete onto the market? So that people start working with it, including on the construction floor — so that the labourer who pours it gets, or has received, the necessary additional training and so on?

Maiko van Leeuwen – 27:30 Yes, the labourer who pours it will in any case need to take extra protective measures. I think that will happen through toolbox meetings — where a contractor holds a toolbox meeting and informs his workers in that area. That is, I think, the established way. What you currently see is that geopolymer concrete is delivered based on composition, so not on certificate. The concrete plant and a contractor agree together: we are going to deliver geopolymer concrete, and you both agree to that. Because you don't have certification yet. That certification is now being worked on intensively, but it simply needs a few years. That's just how it works. Once it is certified, you may simply use it without any problem — because that certificate is a guarantee. So as a concrete plant you also stand behind that certificate. After certification comes verification. That means that BMC Kiwa will come to your concrete plant four times a year to check whether you can still do it. They will then look at whether you comply with the safety rules — that's where you start. Then you proceed to make that concrete with an inspector present, and you have to demonstrate that the workability is okay, and the strength, etc. All of that has to check out. And that you comply with the durability requirements. But that is an ongoing process. That already applies now for all current strength classes and other concrete types. That you have to demonstrate that four times a year.

Sam Meeuwis – 29:30 What do you think specifically needs to change for designers and architects and so on, for them to want to make that switch? Aside from the fact that you see that in education — at architecture faculties, for example — there is barely any teaching about concrete at all. 9 out of 10 of my professors have never heard of the word geopolymer concrete... What do you think is needed there?

Maiko van Leeuwen – 30:00 Well, that means we are doing something wrong somewhere. And I always find that rather amusing. At the university of technology we are always very good at many things: developing new products, conducting high-level research. I can't say otherwise. But we are generally very poor at selling ourselves. We are very poor at promoting our findings. Just to give a small example: if I walk through this building right now and ask 10 students what the microlab is, maybe two will know — but they only know because they know me, and that is the wrong reason. You need to sell yourself much more. You need to make it clear to the outside world that concrete made the old way — that will no longer be possible in a certain number of years. This is the new product, and these are the consequences of using it — positive and negative. That's where it starts. It is all about communication and education. That is essentially the whole story. That professors at architecture don't know about it is not good. That is very unfortunate, because concrete is and remains the most beautiful building material in the world. And I am not objective, I know that — but it simply is. Concrete will never disappear; only concrete is going to change. We constantly have to change in order to keep pace with the changing wishes and requirements of society. It is all about education and communication. I would, for example, very much like to go around to primary schools with a van full of materials and samples to give talks about making concrete — and therefore geopolymer concrete too. Because it is such a wonderful profession, and there is such a severe shortage of concrete technologists — it is alarming. 70% of all concrete technologists are between 50 and 60 years old — my age group — so it is essentially a dying profession, and that is not good.

Sam Meeuwis – 32:30 No, that is certainly not good — especially since I also believe that concrete is not going to disappear, but simply change. You can also certainly see at a training week like this: half of the people sitting there come from the concrete industry itself. They are the driving force behind this research, behind this transition, and that is why I think it is all the more important that that interest is actually even greater.

Maiko van Leeuwen – 30:00 Well, I think the initiative of Professor Ye — who organised that — is truly very important, and that man is also very passionate about it in his own way. He does that really very well. And I actually think you should probably do that more often, and not only us at TU. You should actually see it somewhat more at a European level — maybe even worldwide. Because the same problem exists in other countries too. The second and third world countries will be the last to make the switch. That is related to costs. It is related to the fact that you have to train people — so they always go last. But you have to start somewhere. It has to spread like an oil slick, and a great many people in the concrete industry are already working on that. I see, as a concrete technologist, as a practical man, and as a man who loves the material concrete, that there is really only one way — and that is the way of change.

Sam Meeuwis – 34:30 That training week was called the bridge between the academic world and practice. What I find quite funny is that every image they showed of the research went — say — from the scale of atoms to a bridge. But the area I work in is precisely up to that bridge, roughly 3 scales back, and then further — towards regions, countries, social findings, etc. So the larger scale that comes after that was not present at all.

Maiko van Leeuwen – 35:30 Professor Ye's perspective is an academic journey — he is a professor for good reason — but he will always start with the Xs and Ys, so at the atomic level, whereas we are actually more interested in what you describe: the 3 phases before that, and especially also afterwards — after the pouring. But yes, for that you have a scientist who wants everything chewed over 20 times before he gives his blessing. Now I must say that Professor Ye has more practical experience than you might initially think — because he visits construction sites very often and he genuinely knows what is going on in the industry, so I really have nothing to say about that. He does that quite well.

Sam Meeuwis – 36:00 To come back to the recycling story. We also discussed it during the practical week. Do you think a problem is going to arise during the transition from regular concrete to geopolymer concrete, when it comes back to the recycling facilities?

Maiko van Leeuwen – 36:30 In any case, with every structure — whether it is regular concrete or geopolymer concrete — you have to ask yourself: concrete has a maximum lifespan, or we no longer find the structure aesthetically pleasing and we demolish it. You have to carefully consider what you are going to do with those waste streams. Honestly, I don't know whether you can simply mix geopolymer concrete in with regular concrete. Because that concrete simply has different properties from regular concrete. On the other hand, I also can't really imagine sorting 20 different waste streams in the future. That is not workable in practice. So I think that would be a very interesting next trajectory: can you simply mix them together, and in what proportions? Research needs to be done on that. If I look at our Microlab now, I think 2/3 of our PhD candidates are working on recycled concrete materials. The next step will hopefully be that you start getting projects in. Then you also still have work to do in looking at whether you can simply mix those two waste streams — geopolymer concrete and regular concrete — together. Research simply needs to be done on that. We already know a great many basic properties, because we already do those studies for geopolymer concrete and for regular concrete. But now you have to mix them together. Then you have to say, for example: if I take 75% regular concrete and 25% geopolymer concrete — what are the consequences? I think the bond will not differ much from each other, but in terms of shrinkage, for example, I can well imagine you would need to take that into account.

Sam Meeuwis – 38:30 Do you think research in that transition phase will be leading in terms of how it gets deployed?

Maiko van Leeuwen – 39:00 Yes, absolutely. We are now going to enter the phase — in the coming years — in which we make a great deal of geopolymer concrete, produce it, and create beautiful structures with it. In a number of years you will then reach the situation where it needs to be demolished — and what are we going to do with that? But then of course you need to be working on that already now. Because 20 years always sounds like a very long time, but it goes very fast.

Sam Meeuwis – 39:30 It is the responsibility that you have thought of everything in advance.

Maiko van Leeuwen – 39:30 Yes, certainly — but that is already being thought about, I have to say. We also have a recycling department here within TU that is already doing a little bit of that kind of research. But I think ultimately it will become more research for people in concrete structures and in our department of materials science. And we are simply going to dive into that very deeply. Only yes — for that we need projects. Those you get from the government, from large contractors, and those come with a budget, and then you can take on one or more PhD candidates. They will spend about 4–5 years doing their thing, and then you can investigate many things. That is something the industry is also already working on in their own research centres. The admixture manufacturers are also already working on that. They will, for example, also be getting a new generation of admixtures — because do plasticisers work just as well with geopolymer concrete as with regular concrete? I don't know.

Sam Meeuwis – 40:30 Probably not.

Maiko van Leeuwen – 40:30 Well, that's what you say — but why not? That is also what we want to know. Why not, or why yes?

Sam Meeuwis – 41:00 Yes, "why not" is the most important — but what you do see is that the differences there are very, very large between regular concrete and geopolymer concrete, in terms of the effectiveness of admixtures. At least, based on what I have gathered so far.

Maiko van Leeuwen – 41:00 Yes — the mixing procedure for geopolymer concrete is already very different, and if the mixing procedure is different, it also means you have to approach your admixtures or additions differently.

Sam Meeuwis – 41:30 Yes, that's true — but then it is precisely nice if there is indeed a market drive behind it, so that it gets an extra push.

Maiko van Leeuwen – 41:30 Oh, yes — of that I am absolutely certain. Yes.

Translation by Claude 4.6 Sonnet — original interview conducted in Dutch.

Interview 3: Martin Verweij (demolition and waste processing)
[Full transcript - Dutch original. English translation: see below.]

Interview Transcript 3 – Martin Verweij

Martin Verweij – 00:00 My name is Martin Verweij, from Cementbouw, also from VVM, and from the company Sqape. I am responsible for innovation at Cementbouw in the area of raw materials for concrete — primarily fillers. At VVM in Belgium I help develop sustainable cements, and within the subsidiary Sqape I am trying to bring the material geopolymer concrete to market, to have it implemented and accepted. I once studied chemistry and got to know various materials throughout my career — such as asphalt, concrete, and ceramic materials. Now the focus is on cement and alternative binders.

Sam Meeuwis – 01:00 That is a very interesting combination. You certainly have cross-scale knowledge, from materials science all the way to structural knowledge.

Martin Verweij – 01:30 Yes, and implementation means getting projects off the ground, doing a bit of marketing, but also drafting the regulations that are needed for new materials.

Sam Meeuwis – 02:00 Yes, those are actually already a number of topics that have been discussed a great deal. I think regulation is one of them. In your opinion, what are the biggest obstacles and gaps that still exist for this material to be implemented in the Netherlands?

Martin Verweij – 02:30 Up until now we have worked without specific regulation — or actually within existing regulation. That also leaves room for new types of concrete and new binders, according to the equivalent performance principle. That is already in the Eurocode, it is also in the building decrees. So you may always apply a different material as long as you demonstrate that it is equivalent.

That is immediately quite complicated, because then you have to present thick reports in which sometimes forty properties of a concrete mix have been tested, to demonstrate that it is suitable for that application. Fair enough — that is a possibility — but if you want to apply it on a large scale, you need a kind of certification: one single document stating that geopolymer concrete (from Sqape) is suitable for this and that purpose.

That would be much easier. Who is going to draw up that regulation? That has essentially been the problem up to now. Sqape is a very small company — about two, two-and-a-half people work there, small turnover. And regulation is truly a major investment. We have done some of that from Cementbouw, for example — with a concrete mix containing lava meal, which is a filler based on lava. We paid a great deal of money for that. And what you then see is that the first to do it pays for it, and the parties that then come to you with a comparable product benefit from it. So yes — you really have to be willing to invest a great deal, and also have the confidence that you can recoup the money.

Well, we don't have that yet with geopolymer concrete. We see that everyone is talking about it — sustainable construction, sustainable concrete. But then people find it daunting, because it is complicated and it is still more expensive right now. And then 80–90% of people say: well, let's not bother then, let's go back to old-fashioned concrete. And then I say: so they don't really want it — not if there's no money to spend on it.

Moreover, there is still no national obligation to truly build sustainably. That is coming. This year it is already starting to look as though a MKI ceiling will be introduced, plus a settlement method using the MKI, which will make genuinely sustainable materials more attractive.

So it is starting to come now, but until now there was simply no clear future perspective. A few provinces were willing — Overijssel, Noord-Brabant, Flevoland — and some municipalities — Rotterdam — or companies —

the Port of Rotterdam Authority. They are all already moving very proactively on this. But you can't base a business model on that or make investments on that basis.

Now Rijkswaterstaat has also said: regulation needs to come. They are going to organise that. Well, that then goes very, very slowly. Because a working group is being assembled by CROW. That working group consists entirely of volunteers — people from the field who do it a little on the side, alongside their regular work. And they all have full agendas. With geopolymer concrete, for example, we sit with twenty people or more around the table, and they all need to find time in their schedules. Beyond that, it is genuinely more than just a few meetings. So that goes very slowly.

If there were a budget for that, and full-time professionals were engaged as much as possible, it could go much faster. But yes — who is going to pay for that?

Sam Meeuwis – 06:00 From what I am hearing, the biggest obstacle is therefore market dynamics?

Martin Verweij – 06:30 The fact that it is still taking so long is because too much is being left to the market. If you want something, you have to pay for it. Regulation is typically something that is beneficial for the whole sector. So you need to facilitate that — you should not leave it dependent on 1% of the producers.

Sam Meeuwis – 07:00 Yes, because that creates a kind of threshold that you first have to clear as a producer — one that is too large in scale?

Martin Verweij – 07:30 Once you have incurred those costs, they are incurred and you can move forward. You need that regulation to make it possible. It is simply still a very, very small volume, and you cannot make very large expenditures for that.

Sam Meeuwis – 08:00 What then, in your opinion, is the biggest reason why you say: we really should start using geopolymer concrete? And how could the government — or provinces, for example — best support parties like Sqape?

Martin Verweij – 08:30 Well, for me, you don't necessarily need to prescribe geopolymer concrete specifically — but you do need to prescribe sustainable concrete. That is what I consider most important. It is about sustainability — it is not about one single technique. Geopolymer concrete is the technique with which you can achieve the lowest footprint. That does not apply to all geopolymer concrete mixes — but it does for ours. And mixes are already being cited that have a much better footprint than ours. I think the potential is truly enormous. I also think that ultimately cement will be produced sustainably.

CO_2-neutral — that will just take a very long time. That could still take 10, 15 years. Until then, you can also build sustainably, with alternative binders. Fully or partially replacing cement. But making cement sustainable also costs enormous amounts of money. So cement is going to become extremely expensive in the coming years. If you then have an alternative that is sustainable and considerably cheaper, it becomes very attractive to build with for the next 10, 15 years.

Sam Meeuwis – 09:00 Do you currently see that alternative binders are still operating somewhat in the same market as, for example, ultra high performance concrete or fire-resistant concrete? Because those are a bit of niche markets? Or is it actually a problem that they are competing against the vast majority — CEM3B — and it simply comes down to a price difference relative to how much you need?

Martin Verweij – 09:30 I don't know the ultra high performance concrete market that well. A great deal has been written about certain applications — primarily as a prefab material with which you can construct very thinly, very aesthetically, and to save material — thereby also saving CO_2 — but I haven't seen real evidence for that, though perhaps it is possible. I think that is truly a niche. I don't think we are going to make viaducts with ultra high performance concrete, because with ready-mix transport concrete you are bound to a limited choice of raw materials and production methods. So that remains a kind of 1, 2, 3 concrete, so to speak.

And geopolymer concrete can indeed play a role — but broadly, not in a specific niche of the concrete market, just very widely. I also think it is going to become more fragmented. What we currently do is make everything with two or three types of cement. And even laying bricks we essentially do with very high-grade cement — with which you could actually make high-grade concrete. That is actually not necessary at all. Paving stones are another example. I have discussed paving stones with a great many colleagues. It is an example where concrete comes into contact with a lot of water, and then you have very high requirements for chloride penetration, carbonation, and so on. But testing paving stones for very high strength and frost resistance is somewhat unnecessary. And we make them with the same cement types as structural concrete.

One option for that is geopolymer concrete. At the moment, due to the high requirements, that can't quite be done yet — we then deviate somewhat in the BCF. But we can truly also make interior floors — hollow-core floor slabs, for example. Sometimes they are in a car park, where you have to be careful with de-icing salts and such, but an interior floor in a residential building simply stays dry for a hundred years. There you can use a different binder that is not necessarily exposed to the external elements such as frost and seawater.

Sam Meeuwis – 11:00 Yes, that actually comes back to what John Provis said: knowing how to find the right solution for the right place. And I think that is indeed why I was so surprised that it has not really been picked up seriously within architecture — in the academic world at least. Because this whole range of places where you can apply it — I think there is far more there than in civil engineering structures.

Martin Verweij – 11:30 Yes — what I see in architecture are a few hobby horses, with all due respect. One of them is building with timber. That is then seen as sustainable. But yes — I first need to see where we are going to get all those forests from to build all those buildings.

Circular construction — applying used materials — that is much more sustainable. The fact that you can produce concrete in truly sustainable ways is often not known. And then no choice is made for it either.

So I do think it starts with education. But also with reading trade journals. Enough is written about it — but if you don't read it, you don't know. Then it won't be specified. And I see that everywhere. We have been working in geopolymer concrete for twelve years now, and I also give lectures. Sometimes people come to my class who have never even heard of it... How do you then acquire knowledge about your own field?

Sam Meeuwis – 12:30 Is it important that that is set up as broadly as possible, when it is not yet present there? You see it with timber construction, for example. What you described as almost a kind of tunnel vision among students at the moment.

Martin Verweij – 13:00 Not almost — it is. It is based on assumptions, and there is also a great deal of intuition involved. The feeling that "it is natural, so it must be good" — I don't readily believe in that.

Sam Meeuwis – 13:30 I think that also has a little to do with how we work across different scales, actually. To give a specific example: I have deliberately chosen to keep things strictly within the Netherlands. During the

RILEM symposium there was also a question about that, which you answered at the time: "What about these material streams within the Netherlands? And is there even a future for this material if you look at the use of blast furnace slag and fly ash within the Netherlands?" You said: yes, it is a bit of a misconception that these are locally sourced. Could you elaborate on that a little?

Martin Verweij – 14:30 Well, the blast furnace slag — we think it comes from IJmuiden. But in IJmuiden they purchase iron ores from Australia and North America. So those slags actually also come from Australia and North America, together with coal, and we make steel and slag from them here. And perhaps, from a macroeconomic perspective, it would be more advantageous to produce steel in China and bring only that steel here — and the slag instead of the ores and coal. But you also want your own steel industry.

Fly ash always came from Germany — but the coal also came from China and Australia, so that fly ash didn't really come from Germany either.

In the Netherlands, fly ash is becoming somewhat less available in the immediate vicinity. But I don't yet see many countries switching to cement with fly ash and slag. And new coal-fired power stations are still being built all over the world. So we think there is still at least 10, 15 years' worth of fly ash and slag available. You can use those in cement, you can use them in geopolymer concretes.

At the same time, we are of course looking at alternatives — because if you look globally, there are only a few materials available in sufficient volume to replace cement. That is limestone and clay — so clays — and we are also working on those.

Sam Meeuwis – 15:30 With kaolin.

Martin Verweij – 15:30 Yes — not necessarily kaolin, which is a very pure clay, but all kinds of clay types that are locally available.

Kaolin is somewhat more prevalent in the southern regions — North Africa, one location in southern Germany, and somewhere in France. But we are investigating the local clay types. And also waste streams — that is what your research is also about. Such as the bottom ash from municipal waste incineration — a great deal has been said about that.

The key issue lies somewhat in the reactivity, however. Up to now it has been applied as an aggregate in concrete. Well, that didn't always go well — it could sometimes react and swell. But if you turn it into a filler or a binder component, you are actually making use of that reactivity. Well, if you also remove all the contaminants, it becomes an excellent building material.

If we genuinely talk about the options within the Netherlands — which certainly means working with what is locally available — we see that there is already a great deal that can be done.

And that you can then use much lower proportions of blast furnace slag or fly ash — or sometimes that it is not even necessary. Sometimes, because the volume of concrete is still so large that with those few waste streams you simply won't get there. So there always needs to be primary material as well. But yes, you also first look at the recycling options, because then you kill two birds with one stone with residual streams: you prevent waste and you prevent the use of primary raw materials.

So in addition to that bottom ash, we are looking, for example, at dredging sludge, sewage treatment sludge — those kinds of things. These are things we produce daily as waste, and you can do quite a lot with them.

Sam Meeuwis – 19:00 Is harbour sludge also being looked at — what we currently dump in the North Sea? We have a great deal of that. I happen to be a guide in the Port of Rotterdam, so I know a thing or two about it. Yes, of course it used to be full of contaminants — PFAS and heavy metals. But nowadays it is clean enough that we are allowed to discharge it into the North Sea again. In the old days all of it had to go to the slufter.

Martin Verweij – 19:30 It is being discharged now. That is what the port authority itself wants to and is able to do. Sometimes you also have to be very pragmatic about it. If you can't do anything else with it right now and you still want to keep the port open.

Sam Meeuwis – 20:00 Yes, but they have a slufter where they could store it, and that is simply not being used for that purpose now — because it simply isn't full yet. In a sense that is a waste, because if we stored it we might still be able to use it.

We've now touched somewhat on the topic of lifecycle. If we don't just look at how this is then going to be used as raw materials, but ultimately there is also an important piece of the cycle: the end of the material in its primary use. That is why part of my research is also focused on closing the loop. So essentially looking at a building and asking what can be reused — and actually reimplementing that in this material.

And with that reimplementing of the material, I think a logical choice is actually to reuse stone-like building materials as aggregate. First, of course, reuse the usable components — reuse on a large scale. And that is very important to say, because it means you don't design a beam or a wall for the lifespan of that building alone, but for a number of lifespans.

Martin Verweij – 21:30 Yes, that is important. And it also means that we really need to start taking maintenance techniques seriously. All those bridges of Rijkswaterstaat that are now corroding — that is simply due to a maintenance deficit. That is somewhat of an oversimplification, but because the expansion joints start leaking, water with de-icing salts reaches the bearing points of the girders, which causes them to rust. If you genuinely keep those properly watertight, those bridges will last 200 years.

Sam Meeuwis – 22:00 Is that in that sense also a design fault, or is it genuinely management?

Martin Verweij – 22:30 Management, yes. A fun fact — I don't say this everywhere — but I spent nine years doing damage investigations before this, and yes, it was almost always management.

And what we also do is constantly expose concrete to the elements. If we did that with steel, it would rust within a few years — and then we apply a coating to it. With concrete, we don't do that. So with a layer of just one millimetre you can extend the lifespan of your material many times over. How simple can it be to start doing that with concrete too? There is of course also a difference in that, as we discussed earlier, with concrete used in residential buildings or other structures — because those are simply barely exposed at all. That is indoors, so indoors it is much easier.

But external applications — yes, those we really need to design differently. Maybe even design for a thousand-year lifespan. And then also maintain. With monuments, we do that. For example, the Groothandelsgebouw in Rotterdam. That is very special — built just after the war, and Rotterdam doesn't have many old buildings. Well, if you see how meticulously and with what enormous budget it is repaired annually... suddenly it is possible. So perhaps we should also start treating our structures like monuments.

Sam Meeuwis – 23:00 Well yes, that is what some professors say. If you design beautifully enough and people want to care for it, you essentially achieve ultimate sustainability.

Martin Verweij – 23:30 We need to start designing for a thousand-year lifespan. That is of course bad for the cement industry. But it is true. So design for disassembly. And then you also shift somewhat more towards prefab. Another aspect we have agreed upon in the Netherlands: whenever we have a new raw material for concrete — not just geopolymer concrete, but also those with lava meal or other fillers or aggregates — we have to look at how it behaves after recycling. So we do indeed granulate it, make new concrete with it, and that also needs to still be responsible.

Sam Meeuwis – 24:30 I visited one of Renewi's recycling centres — the construction and demolition waste department in Amsterdam — to look at their concrete recycling. Enormously interesting, but also immediately quite concerning things heard. They also have a great many problems around regulation. On the other hand, they said: 80% of what we receive we are not allowed to recycle because it is too contaminated during demolition. So there is simply too much plastic in it, too many other materials — while there is a great deal of usable material in there that, had it been demolished more carefully, we could have used.

Martin Verweij – 25:30 We need to stop demolishing. We need to start dismantling. What we also did with cars for a period: removing the starter motor, putting the glass aside, mirrors, wheels, etc., for parts. We genuinely need to start dismantling. And yes, that costs money. So if we say: yes, it has to be cheap — then you demolish and mix. But if you say it is valuable and we are going to harvest it — then you need to dismantle.

Sam Meeuwis – 26:00 Yes, and you could really see that there — because I saw the pile of stuff that simply goes away, that they can't do anything with. It just gets pulverised and 95% of it goes under roads in the Netherlands. That is literally just dirty material. And then you also think: if there is so much contamination in it, should we perhaps not be putting that in the ground?

Martin Verweij – 26:30 Well, if you build with it, it complies with the Soil Quality Decree. So it can never be severely problematic. It may contain a piece of plastic and electrical sockets, etc., but you shouldn't then apply it in a nature reserve as a footpath.

Sam Meeuwis – 27:00 But just dumping it under the road shifts the problem to the future. That road will also be demolished at some point. I saw that you had an example of reusing asphalt, I believe — a geopolymer with asphalt granulate. Did you see major differences in the use of geopolymer compared to regular concrete?

Martin Verweij – 27:30 Yes — for regular concrete we usually have access to somewhat rounded aggregate particles. In the Netherlands that is quite unique: a lot of river material that is nicely rounded, gravel, sometimes sea material too. But in asphalt they work a great deal with angular material. And for concrete it becomes difficult to make a mix with that which flows nicely. So the particle shape is a challenge. So essentially you need to make new asphalt with that asphalt granulate. But it can be done.

Sam Meeuwis – 28:00 Is that particle shape a problem? Because I also discussed that with Renewi, and they said it actually comes from — when looking at construction and demolition waste — the way in which it is broken. So whether you roll it or literally crush it. There are of course countless methods nowadays to get it in a shape such that the granulate itself has the properties you would most prefer.

Step 1 is of course dismantling — high-value reuse; let's put that first. But imagine the situation: okay, it genuinely has to be demolished. Or at least the components — their lifespan is over and they need to be reused. Do you think the most important thing is then to make the best possible granulate from it, because we are used to working with that? Or do you actually need to look at: if we break it in the most economical way, then we get this type of granulate and we need to design for that?

Martin Verweij – 27:30 No — you genuinely need to make it as clean as possible. And actually with as low a porosity as possible. Then you need less water and less binder. And the binder in concrete is always the component with the greatest environmental footprint. So it always needs to be as clean as possible. So those innovative techniques are truly very good, useful, and above all consistent. When you develop mixes, you simply want the same quality every day. Otherwise you are constantly making adjustments.

Sam Meeuwis – 29:30 If we talk about transitions, by definition that is not really constant?

Martin Verweij – 29:30 In the long term it is not constant, because change is part of it — but the daily variation should be as small as possible.

Sam Meeuwis – 30:00 Do you think there is something to be said for what large concrete manufacturers say — that they are a little afraid that when these new materials come back into regular concrete, for example, they will cause problems?

Martin Verweij – 30:30 That was a realistic concern, I think. For granulates, for example — the particles from recycled paving stones could indeed cause problems in structural concrete. Not only paving stones, but concrete granulates in general if they contain bits of wood and other things. You want to use them to make a floor and then everything floats to the surface. But if we genuinely start applying the guideline seriously — that we also investigate raw materials in a second life — in structural concrete, which is truly a high-value application — then we overcome this argument. In the first life you can also apply things like elephant grass. And there are all kinds of pros and cons to that. But if you want to recycle that concrete with elephant grass, you have to investigate it properly. And it can't go into the main stream. Then you have to collect it separately and recycle it separately. But if you say: let them figure out how to recycle it — that is of course wrong; you do have a responsibility.

Sam Meeuwis – 31:30 That is certainly also a paragraph in my research now — indeed essentially a responsibility from within the construction industry itself. To document it properly and ensure that it can indeed be dismantled. And in the case of demolition, to know what it is. Because yes, ultimately, if we look a hundred years from now, you can no longer tell from the outside of a geopolymer whether it was concrete or geopolymer, probably.

Martin Verweij – 32:30 Yes — biochar is similar in that regard. So there is already CO_2-neutral concrete — it contains a kind of charcoal. That block, that structure, can be CO_2-neutral, but just try recycling it. You already almost know what will happen... But that simply needs to be researched. I am not saying you may not apply it — but you really do need to research that second life properly. And then, in my view, it is responsible.

Sam Meeuwis – 33:30 When we look at the design engineering side of second lives: is there an argument, in your view, for intentionally over-engineering elements? So deliberately making them much stronger, perhaps with slightly larger dimensions, so that the degree of freedom is simply somewhat greater?

Martin Verweij – 34:00 Well, one step back — you need to start designing for a much longer lifespan. And that can mean higher quality concrete, more cover — then it gets very technical now. Or, for example, reinforcement that cannot rust — then you have solved it too.

Sam Meeuwis – 34:30 If you then ask the recycling facility about that, they say it is a bit of a nightmare — because it doesn't break out cleanly and it always stays in. Plastic reinforcement, for example — I genuinely heard complaints about that at Renewi.

Martin Verweij – 35:00 You do have alternatives — basalt, for example, which is something different again. That also needs to be investigated. And stainless steel reinforcement is also sometimes used in offshore structures. Stainless steel is not magnetic, but you can separate it in another way. But yes — you actually need to set requirements not at the level of composition and materials, but at the level of performance. So we want to make concrete that lasts, for example, 200 years, and after those 200 years it must either be reusable or recyclable. Well, if you stick to that, things can almost not go wrong. And then you also open the door to innovations.

Sam Meeuwis – 35:30 It is certainly the case that when you design for a 200-year lifespan, you are designing for something that is completely outside your own lifetime — and then you really have to think very differently about what you are designing and why. And essentially sketch out a kind of future, and have a vision very clearly formed already — because otherwise you make assumptions that are not based on anything, of course.

Martin Verweij – 36:00 Yes, I also think that our profession — your profession, my profession — becomes endlessly complicated as a result. But I do think we will get through it with AI. So if you say: I want to create a building that looks like timber on the outside and it needs to last 500 years — you don't need to think all of that through yourself. I think we can make huge strides with AI on that front. That AI becomes a very useful tool to look up certain things very specifically. In my training I got to know something like three types of cement. Well, we are adding ten, fifteen types of binders — not even just cement. You can no longer capture that in tables — it has to be done differently.

Sam Meeuwis – 37:00 Yes, you can actually see that right now from TU Delft — I saw it in the lecture: there is an AI calculation model, literally meaning AI systems are being built to take a certain input and produce an expected output. I think there is genuinely a very large market in that, and also perhaps a very significant academic leap can be made. That it simply accelerates the process of materials research enormously — that is of course very welcome.

I noticed in your lecture a number of slides going by with actually quite a few examples of geopolymer in the Netherlands. Was all of that exclusively Sqape?

Martin Verweij – 37:30 Yes, I genuinely used our own projects. You saw them come back at Rijkswaterstaat too, because there are not that many producers. So here and there you might see something from a colleague going by, but within the Netherlands we truly are the market leader.

Sam Meeuwis – 38:00 Are there perhaps some examples or those slides or something similar that you could share with me, so that I can actually use them as an example to show: look what is possible?

Martin Verweij – 38:30 Look — as long as there is no commercial purpose involved, certainly. We have also had someone before who said: I make geopolymer concrete — and showed photos of ours alongside it. That was a bit strange. Architecturally it doesn't amount to a great deal yet — it is mainly civil engineering shell structures of houses, etc.

Sam Meeuwis – 39:00 To wrap up the interview a little. What do you think, in summary, are the most important things that now need to happen in order to say: we really do need to change something. How we build with concrete in the Netherlands and how we should shape that going forward — with, among other things, as we hear from you, geopolymers?

Martin Verweij – 39:30 Yes, well — we need to start building sustainably. Everyone can do it, but it is going really far too slowly, far too small in scale. So if you want companies to genuinely make big strides as well, then some regulation has to come. For example — if we have to build a factory to fire clay, that will cost us tens of millions. Then you want to know at some point: are you going to recoup that in two years or in five? That is very simple. And it doesn't have to happen overnight — but there does need to be a step-by-step plan: for the volume we are going to produce sustainably per year. And money needs to come with that.

And Rijkswaterstaat has also once said: yes, then we'll just build less — better two locks sustainably than three in old-fashioned concrete. That is a bit of an oversimplification, but you do need to think about it.

Sam Meeuwis – 40:00 Yes, I think that a step-by-step plan is indeed already a very good example — it starts there with, on a professional scale, doing something like what I am doing for my research: simply mapping out what exists, what the possibilities are. Because yes, if you don't have that yet or don't know it, then a step-by-step plan naturally becomes very difficult too.

Martin Verweij – 41:30 Well, a step-by-step plan doesn't need to go filling in specifics like: we are going to build with timber or with geopolymer concrete or we are going to lower the MKI — but it should steer on end results. Ensuring that everyone has the right knowledge, because you can mandate things, but people do need to have knowledge of them.

Sam Meeuwis – 42:30 Yes, it is interesting that you say that. I happened to have discussed that with Maiko van Leeuwen — so that is the concrete technologist within TU Delft. And he says: if we go and do this, it becomes so complicated. There will then really need to be extra training for the entire range of people who work with concrete.

Martin Verweij – 41:30 Yes, and to add to that — we have been educated for 80 years with knowledge from the cement industry. With all due respect, but that has always been somewhat one-sided. And they still have a great deal of influence. So a great many things you read are somewhat coloured by cement producers. The concrete industry really needs to emancipate itself. And develop genuine knowledge. Well, if you look in the field, that knowledge is almost completely absent. So a concrete producer — they make concrete. Yes, that isn't so very difficult. You have a number of ingredients and if you have a problem, you go to your cement supplier and they have the solution. So a form of emancipation needs to take place. In the concrete world — of genuine knowledge. I think that is in any case the most important step, indeed. From academic — how does it work — to practical — what can you do with it and what can't you. And having the frameworks clearly defined through regulation and financial instruments.

Sam Meeuwis – 43:30 I have an interview with Rijkswaterstaat tomorrow. So I am curious how they experience it — because they are naturally somewhat closer to central government and I think have somewhat different tools in their repertoire to draw upon.

Translation by Claude 4.6 Sonnet — original interview conducted in Dutch.

Interview 4: Sonja Fennis, Rijkswaterstaat (structural engineering and infrastructure)
[Full transcript - Dutch original. English translation: see below.]

Interview Transcript – Sonja Fennis, Rijkswaterstaat

Fennis, Sonja (RWS GPO) 0:22 My name is Sonja Fennis. I work as an advisor in the bridges and viaducts department at Rijkswaterstaat. I am part of the organisational unit for major projects and maintenance, and our unit also does a great deal in terms of knowledge development and research when it comes to the concrete we need for structures. I have a coordinating role in that area. What we did several years ago was to translate the Concrete Agreement — aimed at making concrete more sustainable — into a plan for how we want to approach this at Rijkswaterstaat. That plan is focused on Rijkswaterstaat, but as you already mentioned, because we have this knowledge department at Rijkswaterstaat, many other government bodies and organisations simply look to us for guidance. We have quite a number of people with this kind of expertise. The plan outlines 6 key priorities for sustainability.

1. Extending the service life of existing structures.
2. Reusing elements and components at the structural level of existing structures.
3. Building new structures in a modular way and ensuring they can be disassembled and easily adapted.

Those first three are at the structural level, and then there are three things at the material level:

1. Materials with a very low CO_2 footprint, such as geopolymers.
2. Material recycling — turning used concrete back into recycled aggregate, and also reusing aggregates in new concrete.
3. Alternative reinforcement.

Those are roughly the 6 priorities we focus on in order to meet our sustainability goals. And today we're specifically discussing the one where we say: we are looking for new materials with lower CO_2 emissions. Geopolymer concrete, which is what we're talking about, is simply one of the potentially promising options for us in that regard.

Sam Meeuwis 2:53 That is very, very clear. Thank you for the introduction. I think all three of the last points are relevant to my research. Except perhaps alternative reinforcement, but the recycling aspect certainly plays a very significant role in my research. And in a sense, in the design part of my research — which will follow — all three of the first points come through very clearly. In your view, or from what you see at Rijkswaterstaat, what is the biggest reason, beyond CO_2 savings, for choosing geopolymer concrete — or is there even one? Why would you choose it?

Fennis, Sonja (RWS GPO) 4:02 Beyond CO_2 savings? If it weren't for the CO_2 savings, would we choose it? No.

Sam Meeuwis 4:09 That is interesting, because on the academic side you hear people advocating for it because much better performance is possible in many other areas with geopolymer concrete. It is not one material, but a whole range of materials, which is what makes it so interesting to them. I am trying to somewhat break through the idea that it is only about CO_2. But many parties keep coming back to that point.

Fennis, Sonja (RWS GPO) 4:47 Let me try to explain why we would not choose it otherwise. You really have to go back to the fact that Rijkswaterstaat is an asset manager — when we build something, we build it for a genuine 100-year lifespan. That means that before we build it — and I'll use the large lock at IJmuiden, which contains geopolymer concrete and which we constructed, as an example — I don't want to encounter a problem with my concrete there next year or in 10 years' time. That means the concrete must perform exactly as we have been used to in the past, so that we can calculate with it reliably and it also behaves accordingly. When we now look at the geopolymer concrete mixes available on the Dutch market and the findings we receive in reports and research, we quite frequently see that certain mixes show a decline in tensile strength and a decline in the E-modulus. The E-modulus reduction in particular we see in a great many mixes. This may also be related to a different deformation behaviour of geopolymer concrete, specifically in the area of shrinkage and creep. I'm not entirely sure. I think it could be related to drying. I don't have firm evidence for that yet, but the fact that those 3 parameters are not yet consistent over time, and that we find it so difficult to predict what that means over a 100-year period, represents a very significant risk for us as an asset manager. That leads you to say: I will only genuinely choose such a material once I have sufficient confidence in it. At the moment we see that the Sqape mixes — which you discussed with Martin Verweij — are more recently developed and that we could apply them with a relative degree of confidence. But there are still a few things we say we do not yet know. Things we would need to know first. One relates to the recyclability of geopolymer concrete in the future — whether we can crush it again, turn it back into aggregate, and reuse it. That is still somewhat of a problem right now. Product passports / material passports are not yet in order — that is also still a barrier, a reason why we might not apply it. But that is a very different kind of barrier. If you later knew exactly what is where and you know which recycling facility to send what to, it becomes easier. But if that is not yet the case and geopolymer concrete could end up under the road — it could start leaching, just to name something, I'm not sure — you don't want that. And if it were to re-enter your concrete and subsequently cause alkali reactions due to the high alkali content, you don't want that either. These are still the open questions at the back end that we haven't fully resolved yet. And something else that is also relevant to us — and I'll give a completely different example, but perhaps it will help you understand — we are also not yet 100% certain what we need to do in terms of the management and maintenance of geopolymer concrete, including, for example, repair mortars. For steel, we prescribe a specific steel grade. Why? Because the higher-strength steel grades are extremely good and extremely strong, but you cannot weld them on site to a structure. If you have to come back to such a structure 50 years later to carry out emergency repairs and you ask a welder whether he can weld it, he cannot do that with those very high-strength steel grades. We use a lower-strength steel grade, of which we need a bit more, but which we know we can still manage and maintain over those 100 years. Our management and maintenance period is absolutely crucial to how and what we procure. When we acquire a structure, those structures ideally need to last 100 years with as little management and maintenance as possible.

Sam Meeuwis 9:35 An example like that — the steel grades in use and maintenance — that is precisely the architectural engineering aspect we are looking for. If it then turns out that, with geopolymer concrete, the bond to steel is, for example, less good, or that the workability of steel combined with concrete does not match well, then that has a design impact.

Fennis, Sonja (RWS GPO) 10:05 Let me give a small example. We occasionally have a collision — a lorry drives into a bridge and the underside of the bridge is damaged. We currently apply a concrete repair mortar to that. That is already not very aesthetically pleasing, right? From an architectural point of view you would be horrified, but it is simply applied to continue protecting the reinforcement. If we can't easily do that with geopolymer concrete in the future — because the bond is not good, or we need a special mortar for it, or the person who turns up with a bucket of mortar thinks they're seeing regular concrete but it's geopolymer concrete and grabs the wrong bucket — those are the kinds of things that genuinely factor into our considerations about whether or not to implement something. One of the things we thought about in the beginning was that many early studies genuinely claimed geopolymer concrete is much better in terms of fire safety. We also looked into that, but have not specifically tested it yet, because when we carry out a specific test for that, the requirements are either extremely high — or there is no specific fire safety requirement. That is the case for bridges and viaducts. Or you have very high fire safety requirements, which applies to tunnels. And those very high fire safety requirements for tunnels are almost exclusively met only if you also make it fibre-reinforced concrete. That could ultimately be done with either geopolymer concrete or regular concrete, but you at minimum need those fibres — geopolymer concrete on its own would probably also not meet the requirement. Because the requirements we impose for two hours of fire safety in the major tunnels of Rijkswaterstaat are so enormous that no type of concrete can currently meet them.

Sam Meeuwis 12:08 Is that really a fair comparison, because part of my research is also about how you should compare geopolymer concrete? In the Netherlands we use a lot of CEM3B, for example. Do you want to use it for the bulk category, or do you want to say it is more of a niche application — especially since some of the mixes potentially have these kinds of qualities? That you actually need to compare it with high-performance concrete or indeed fire-resistant concrete?

Fennis, Sonja (RWS GPO) 12:47 You should use your material where it performs best in its own application. Then you want to move away from the term "bulk concrete." Suppose geopolymer concrete is not fire-safe enough for a Rijkswaterstaat tunnel, but it is for an interior wall in a residential building or for high-rise construction — then it is a tremendous advantage. It's just that our fire safety requirement is absurdly high. So you have to ask: where can I apply this material in the best possible way? We had a small example from the congress we attended, where someone had added metakaolin clay or something similar to the mix and as a result it was red in colour. That might be fantastic for use in cycle paths, because then it is already red. Those kinds of things — where you really think about using your material in a smart place. There is also enormous debate in the Netherlands about blast furnace slag. You can take high-quality blast furnace slag and put it in blast furnace cement, but we also know it will not remain infinitely available as a raw material. If the steel industry electrifies, we will no longer receive the blast furnace slag we currently get, which means we will also have less blast furnace cement, which means we may revert to Portland cement. Should you then compare blast furnace cement with geopolymer concrete? Or should you compare Portland cement with it instead? If the slag is not used in blast furnace cement — or if different types of slag are used in geopolymer concrete? People say: it is better to put them into concrete while they are still available. That is the cement industry's position. And then the geopolymer concrete industry says: but we use much lower-grade types of slag. They are not at all the same as what you use. There is genuinely quite some debate about this. You can also look at using different raw materials at specific locations. You can use slag other than blast furnace slag, or you can use combinations of blast furnace slag, fly ash, and other raw materials.

Sam Meeuwis 16:01 Ultimately, precisely what you are describing is so interesting — because it is not one material, but a whole range of materials. They are different raw materials with different properties, which also makes the potential of the mix design so much greater.

Fennis, Sonja (RWS GPO) 16:22 It is an incredibly complex playing field. Because you have a whole range of mix designs that all still need to be developed, and that is something we also find quite complicated — because it is genuinely very complex from a chemical perspective. I have two people here in the office who are much better at all of this than I am, who truly understand the chemistry of geopolymer concrete. But the range is so broad that it is very difficult. Currently there are one or two mixes somewhere that are already relatively well developed — such as the Sqape ones — on which a great many tests have been conducted, while the whole other group is still essentially at laboratory level.

Sam Meeuwis 17:16 I think that is partly attributable to market dynamics — because I heard yesterday, for example, that it also simply costs a lot of time and money, and that you then get a kind of "bet on your best horse" behaviour from the market. And that the initiative from the government is simply not strong enough to push these kinds of things to the market in order to be able to compete with regular concrete at all. It would be very interesting if you found that you, for example, think about this very differently, because the ties with the government are so much shorter.

Fennis, Sonja (RWS GPO) 17:59 No, but there are a few things at play in the interaction between us and the government. The government, by the way, has had an entire subsidy scheme for geopolymer concrete. If someone was going to apply it, they could actually receive money back. The government has genuinely done something to stimulate certain things, but it all stems from sustainability. We are still talking about CO_2 — it is not about other technical aspects. But now I am speaking more from my role as a commissioning party. We also build bridges and viaducts, and you put a contract out to market and you are allowed to specify what you want. If I wanted to, I could write: I specifically want geopolymer concrete. But you are always required to carry out an open tender. I cannot write: I specifically want the Sqape mix, even though I know it is the most developed mix. That makes it quite complicated. It is about a level playing field that is equal for everyone. I could say that for the geopolymer concrete we want, a research report must already be available with compressive strength, tensile strength, and a modulus for shrinkage, creep, etc. That way I would at least have excluded a whole group, and I could then tender on that basis. Even so, you will see that in our case it doesn't happen that easily. The costs for geopolymer concrete are currently very high. I don't think it's the actual raw material costs. It really isn't the material costs either, and it's not that it is so much more expensive to produce this material than traditional concrete — but you are still in that development and scaling-up phase. A party like Sqape has invested enormous amounts of money in carrying out all those tests for their material, in order to bring it to market. What we would most like from the government or commissioning parties is what you might call deal flow — being able to say: we have invested this and this amount, but we know that we will at least be building 10 bridges with it or something similar, because then you can spread the investment costs across those 10 bridges. That currently isn't possible, because they don't know they will get 10 bridges, and we are not allowed to promise that to them, because that would not be an open tender. It is quite a complex playing field. I know that the Port of Rotterdam — also a major commissioning party, but a private one — does do this. They genuinely specifically request geopolymer concrete. And I believe they even go as far as specifically stating it must be Sqape geopolymer concrete of this and that type, and they simply include the mix number as well.

Sam Meeuwis 21:50 What I heard was indeed this story, but also that they have indeed spent so much money, and that all other producers or researchers of comparable mixes then say: but Sqape has already done this. They have borne those costs — we don't need to do all of that anymore. Beyond that, they say the main issue lies with contractors and project developers — that they are still too cautious about using it. Which I can very well understand, especially when you look at Rijkswaterstaat projects, bridges and the like, where the requirements are indeed enormously high and everything is exposed outdoors. But what if you have a hollow-core floor slab in a residential building? I discussed that with Martin too. It simply stays dry. It sits inside a building. In principle, no one will ever access it during the entire lifespan of the building. That is a much lower threshold, and it is certainly interesting to look at those kinds of applications, precisely because they are so different from what it is currently being used for. That is why I found it so remarkable that I was the only person there from an architectural perspective.

Fennis, Sonja (RWS GPO) 23:44 That sometimes surprises me too — that at conferences and similar events I see a great many people from the infrastructure sector. Is there more room for innovation there, or something like that? VBI once, in the early days of geopolymer concrete, built what I believe was the first building with geopolymer concrete hollow-core slabs, and then they pulled the plug. I don't know exactly why. You then often see that the plug gets pulled entirely in that industry for the whole group — but that isn't entirely fair, because it happened to be that one project that didn't work out so well. Because everyone calls it "geopolymer concrete" as a whole — which is the correct term, but it is a family of materials — and everything that falls under it gets lumped together.

Sam Meeuwis 25:35 I also think it is a strong argument to call it: low-CO_2 concrete.

Fennis, Sonja (RWS GPO) 26:11 "Alkali-activated material" would be more accurate, but that just doesn't sound very appealing in Dutch — while concrete itself is also highly alkaline. "Alkali-activated" may actually be a bit more specific than the term "geopolymer concrete." This is actually one of the reasons why we don't specify it. At the moment it is expensive because the alkaline activator is quite costly. We think that as it develops further in the future it will become much cheaper and will suddenly be less expensive. But when I am currently involved in a project and I need to specify a concrete through open tender using public funds — concrete that costs 1.5 to as much as 3.5 times more than regular concrete — we simply cannot get that through in the contract formation. To some extent, you could say: it comes down to how much you are willing to pay for better properties. That could be CO_2. But it could also become interesting if I could perhaps say that geopolymer concrete lasts 200 years. But because I cannot demonstrate that yet, that is the key difference. The producer says: I can make this mix now and you get a 10-year guarantee on it. That is the area where you carry the risk. We have 100 years of asset management, and the risk is much greater at our scale, while contractors sit somewhere in between. That is sometimes what makes it so difficult — just getting it out of the laboratory at all. That is often the hardest step: breaking through that barrier, getting it applied outdoors a few times first, and building confidence from that.

Sam Meeuwis 28:45 When you look at quality assurance — which we've been discussing — do you see a big difference between in-situ use and prefab?

Fennis, Sonja (RWS GPO) 28:59 My impression is that the geopolymer concrete mixes we currently know in the Netherlands are less robust than traditional concrete. By that I mean: if you have to drive an hour to the construction site and it turns out there's something slightly off with the workability of the mix, someone may well want to add a few litres of water or something similar. With traditional concrete that was a nuisance, but not a huge problem. With geopolymer concrete, that is an enormous problem. The second issue is that geopolymer concrete is highly dependent on the way it is processed on site — if a certain temperature is introduced, or water gets in, or it is not cured properly, things go wrong quickly. All of this relates to the robustness of your mix. Since the robustness of these mixes is currently not as well developed as it is with traditional concrete, we don't yet know what adjustments to make when you arrive on site and something is wrong. Aftertreatment / curing, for example, is also still something we describe as being genuinely in its infancy. That is why prefab is currently much, much more interesting — because you can do it under controlled conditions. You can do it with the same construction crew every time. People who are trained and instructed in it, who know how to handle it. And the open time of your mix does not need to be as long, because you don't have the transport period. For now, prefab is considerably easier. But what if you genuinely need to work on site?

Sam Meeuwis 31:15 That is my view on this material as well. I also think that applying those various core qualities is closely linked to how good the conditions are for the workability of the material. If you can maintain those conditions, then precisely what makes the material better comes through more strongly — simply because you eliminate that difficult variable.

Fennis, Sonja (RWS GPO) 31:44 The amount of alkalis applied in the material is very sensitive. If you have too much, you get a kind of E-modulus deformation problems: shrinkage, creep, et cetera. If you add too little, you don't activate it sufficiently, and that in turn affects your strength. You can be far more precise about this in a prefab situation. But what you can also do more easily with prefab is to devise a system where the material is cured at a higher temperature. You do also need to carry out the CO_2 calculation, because it costs CO_2 to generate that heat — but perhaps that works out very favourably. In that way, with prefab you have many more options to play with and to get those combinations right. You can keep it under much better control. When it comes to quality assurance: quality assurance in prefab is simply much easier to organise.

Sam Meeuwis 33:02 The most important thing I am hearing is that it really does come down to the curing process — also in terms of mitigating shrinkage and the like. If it works in a lab, then in principle it should also be achievable in a prefab situation at larger scale. That is my view on it. To wrap things up a little: what do you think — or what is your opinion on — what the next steps should be to potentially use geopolymer concrete in the Netherlands? Do you think active steering is needed? Do you think a step-by-step plan should be developed?

Fennis, Sonja (RWS GPO) 34:00 That is difficult. I can say what we at Rijkswaterstaat are steering towards. We are actively promoting that this material currently be used in experimental settings — not at the largest and highest-risk locations, not in that tunnel or that bridge, but for example as a low-risk application. I believe there is now another project involving impact protection blocks. We also have geopolymer concrete covers at locks — these are components of our regular projects where we think we can help with scaling up at limited risk. Rijkswaterstaat is in favour of this. There are however two caveats. At the moment we are still researching what we can do regarding the recyclability of this material, and whether that will ultimately become a problem, and the research on management and maintenance, repairs, etc. is also still ongoing. That is one of the reasons not to scale up aggressively just yet, and why we are also cautioning that we want to wait for the outcome of this research. The second is that we caution that one mix is not the same as another. That does not detract from the fact that it is wonderful that Sqape has done all those tests. But it does not mean it should be acceptable for producer X to say: but Sqape has already done all those tests — I have a mix here, I've determined a similar compressive strength and tensile strength, and that is sufficient. That is not how it works with geopolymer concrete, and that is a very important warning. All Dutch regulations, concrete standards, materials related to concrete — everything is back-calculated from compressive strength, because there are such nice relationships between compressive strength and the E-modulus. That assumption needs to be abandoned first for geopolymer concrete, and people need to realise this. Furthermore, you need to carefully consider which technical properties are required for the application in which you are using it. Because in a residential building with a hollow-core floor slab, the test for freeze-thaw salt resistance is completely irrelevant — whereas for a viaduct it is very relevant. I have seen geopolymer concrete mixes that people wanted to apply outdoors already, where I thought: you are still at laboratory level. The level of knowledge about geopolymer concrete in the Netherlands still needs to improve somewhat.

Sam Meeuwis 37:17 I also think additional knowledge is needed across all areas: among producers, researchers, the people working with it on site or in the factory, those carrying out maintenance, and when the material enters the recycling cycle. Across all those areas I indeed see that things still need to change, and that there is still a lot to be done to get everything properly sorted. Perhaps then the answer is indeed to create a step-by-step plan in which — based specifically on science — it is stated: these and these raw materials have the highest potential in the Netherlands. The mixes should be based on these, and instead of the current 3 concrete mixes, you end up with something like 15 mixes for geopolymers. And once those have been worked through, we simply have 15, and we can always look at additional options later. Otherwise, in my view, you will never be able to bring it to market and compete.

Fennis, Sonja (RWS GPO) 39:31 It really is a matter of taking certain specific mixes — suited to specific applications — genuinely developing them further, and also making use of their specific advantages.

Translation by Claude 4.6 Sonnet — original interview conducted in Dutch.

Interview 5: Mika Autio, CRH / Finnsementti, Finland (industry application)

[Full transcript in English - see submitted document]

Interview Transcript 5 – Mika Autio (CRH)

Sam Meeuwis – 3:22 You are from CRH. Therefore, I think it's very interesting to talk with you. I think you have a viewpoint which is much broader than my research, but is able to answer some questions of my research. It's interesting to dig a little deeper than where the scope of my research ends, to give a better understanding of what the underlying actors and factors that drive the research and the use of these materials now are. So I think it's best if we start with a very short introduction of yourself and what you have to do with geopolymers or concrete.

Autio, Mika – 4:00 My role in CRH is that I'm a programme manager in the Innovation Centre for Sustainable Construction. Our team's purpose is to research and try to find what new technologies exist in the cement and concrete industry. For example, we are very interested in all the new technologies that improve the sustainability of concrete — like the name says, Innovation Centre for Sustainable Construction. Geopolymers are of course a part of it. In our team I am responsible for the geopolymer projects, which means that I'm giving some technical support to the operational companies that are already using geopolymer concretes in their production.

I am also in contact with different external companies that offer geopolymer technologies. I'm talking with them, trying to understand what they're doing, how they could benefit us, and also helping them to work with our CRH companies. Geopolymers are still rather new in the field. There are new companies popping up that either are using the technologies that are already there, or they have developed their own technologies based on new raw materials that are not commonly used nowadays. For example, the use of different types of steel slags or copper slags — that type of thing. It's very interesting right now because those types of slags are waste that we currently cannot use in concrete production. But there are some technologies that can utilise them as geopolymers, and that is very, very interesting to us. All the GGBFS, fly ash, and the type of precursors that are most commonly used in geopolymers can already be used in concrete production. So if we have a technology that can tap into these new waste sources for our use, that can be very beneficial for us. For example, one thing that I do in our team: we will have to validate that these technologies actually work. So I will be doing that type of work in our laboratory, for example.

Sam Meeuwis – 7:12 So that's exactly the aim of my research. For my research I'm looking at a holistic approach for the Netherlands — whether it's viable, whether it's workable, and whether the flows are enough and good enough. Whether they are qualitatively and quantitatively sufficient to have an actual scalable product. But also intertwining all the other flows that exist in the built environment — for instance, reusing rubble from demolition as new aggregates.

So I'm in contact with recycling facilities within the Netherlands, talking about their flows. And within the scope of this research, I aim to look at how innovative, low-CO_2 and reusable we can make geopolymer concrete. So is it possible to make a 100% recycled material? Which is actually maybe possible, looking at all the flows. So that's one of the big pillars in the research. One of the other pillars is how to produce — how to make things with them.

What are the qualities? What architectural expression does that ultimately imply? And then it also has to do with stock. How are you going to use it, and how are we going to redefine and build with it, and what needs to change? So all those combined seem to push in favour of actually using geopolymers, and there's a very good chance that they are going to be adaptable. But the research is not there yet — that's the general gist now.

And if we want to work with it, then we have to overcome very specific geopolymer-linked problems that we don't have with normal concrete. That brings me to one of the main subjects in my research: the comparison with ordinary Portland cement concrete and ultra-high performance concrete. Why I chose both is because I think there's a distinct difference between the technical performance — which you can compare quite easily — and other performance factors. I think that you don't have to compare it quantitatively on, for example, compressive strength, because the chemical workability is completely different for these materials. I would also like to compare it qualitatively: how they act now in the market. So that's where the UHPC comes in, because it's a more niche market and I think it's more suitable to make a comparison within that framework — and you actually see where geopolymer concrete is now — than to say geopolymer concrete has to match OPC, which is simply not doable. That's also not the case, I think. I was wondering what your opinion is about the way we're working now with these concretes. What are the differences between OPC, geopolymer concrete, and very niche products like UHPC?

Autio, Mika – 11:34 Definitely the best way to go about this is: these are all very distinct, different products with different properties, and I think for each you can find a niche or area where they are the best. For example, ordinary Portland cement concretes — they are very good as a big, bulk, high-volume product. Products like UHPC, like you said, are very niche: you can use them in certain applications. For example, high-rise buildings commonly use them in certain places where the performance of the normal concrete types is just not enough. Geopolymer concretes are still maybe a little bit finding their place. There are certain places where they can outperform OPC. For example: chemical resistance. In certain conditions — for example, if we have an acidic environment — then OPC is just not performing well at all, and there maybe geopolymer concrete can in the future play a somewhat bigger part.

But how it is right now is that geopolymers come into play whenever there is the need for ultra-low carbon solutions. And that's kind of the thing we know geopolymer concrete for. It is something that UHPC applications cannot do that well. Yet of course you can do it with OPC CEM3C blends where you have only very, very little clinker — there you're mostly using, for example, GGBFS and can therefore achieve very low carbon footprints as well. But they have very big problems with workability and strength development, where it's just not very easy to do in high volume. So yeah, in my opinion, for each of these applications you need to find the area where they perform the best and just use them there.

Sam Meeuwis – 14:11 I think that's also the main message said at the symposium: "the right material for the right job at the right place." I think that's the engineering question that needs to be solved every time you have a new project. Is this the right material for the job?

Autio, Mika – 14:36 Yeah. And it's not only about OPC, geopolymer concrete and UHPC — but it's also about the use of timber, use of bricks, use of steel, whatever it is: the right material for the right place. That's something that needs to be done always and at all scales, so that you use the raw materials — whatever they are — most efficiently.

Sam Meeuwis – 14:58 I think that's the key ingredient to actually making durable and environmentally friendly buildings. So you were talking about the chemical resistance of geopolymer concrete — that's something I actually had not heard that much about before. What are, in your opinion, the most promising pros and also the least promising cons of geopolymer concrete, if you compare them with OPC?

Autio, Mika – 15:41 I would say that the most promising part of the geopolymer concrete system is its promise of versatile use of new waste material. There are different types of metallic slags which OPC systems simply cannot use. We can think about the use of mine tailings. A couple of new companies have popped up. In some cases there are actually even some new applications that can also use different types of rocks to make the binder — non-limestone types. They are claiming that you can just take, for example, granite, grind it, and chemically activate it.

That's huge — hugely exciting if it's true, and if it works. So that's one part where I see very big things for geopolymers. And yeah, the chemical resistance in certain cases can also be a huge thing for those niche applications. For example, if you are making pipes for wastewater — that's a really harsh condition for OPC where geopolymer concretes can outperform them by quite a bit.

And the negative parts, I would say: most of the current technologies are relying on very harsh chemicals. That is a big problem — using geopolymer concretes is very difficult, very dangerous. There have been some workplace accidents where people get burned from the activator chemicals, and that is a big problem. So far, the financials are also a problem, since the activator chemicals can be really expensive and the price of GGBFS has been going up. So getting them to be a financially sensible option is difficult in the construction business. The price is very, very important because we are using huge volumes. If you think about making one cubic metre of concrete: if your recipe's price goes up by 1 euro — it doesn't sound that much, but if you have a project that uses 50,000 cubic metres of concrete, that's already a price increase for a project of €50,000. So you have to think in huge volumes, at least on the financial side.

The last downside is also definitely the question about long-term performance — whether it is the shrinkage, creep, or the micro-cracking that has sometimes been observed in geopolymer concretes. It is something that might essentially block the use of geopolymer concretes in critical construction quite a bit. If the engineer cannot be sure that it will last for 50 years, then possibly it's better not to use it.

Sam Meeuwis – 19:40 I think all the things you said are exactly spot on. One of which I want to explore a little further is the pricing. I think that with the raw materials now, what you see is that some of the raw materials — for instance, blast furnace slag — can sometimes be so overpriced that the actual material becomes way too expensive. But that's also due to the influence of the OPC industry on those pricings. So do you think that to compare them at this stage and say "they are more expensive because the new resources are getting more expensive" — is that fair to say when you have such big monopoly players in the field?

Autio, Mika – 20:34 Actually, that's what's driving some of these prices. It is all about the loss of availability and demand — because in the concrete industry, one of our biggest challenges and biggest drivers in our field right now is the reduction of carbon footprint, and GGBFS is simply the best way to do it.

So all of the GGBFS that is produced is wanted for use in OPC. So if you have a source for it, there are already a few different big players competing for it. And each one of them is ready to compete on price. And since each of the big players — let's say CRH — is hoarding their materials, the others each want it, and each one is ready to pay higher prices for it. So of course that drives up the price by a lot.

Sam Meeuwis – 22:10 I think that's of course true, but shouldn't there then be a European — or maybe national — level incentive for companies which are using quite novel materials like geopolymers, to actually get these raw materials with either financial support or with some kind of easier access? Because otherwise you will never be able to get over the first hurdle of developing a new material. Or do you think that this transition is driven from the cement industry and they are able to drive it forward — so there shouldn't be an incentive because the incentive is already there, with the market players that are settled in the market now?

Autio, Mika – 23:27 No, I don't think so. I think first of all it's fair — but that would be quite questionable when you think about the competition laws in Europe. But even from an environmental point of view, I think that wouldn't be the way to go. If you're thinking about what low-carbon concretes and geopolymers are both doing: they want to replace the use of clinker. And if we think about the starting situation where we are building, let's say, 100 buildings that are using 100 units of OPC — so let's say pure clinker cement — you take a low-carbon concrete that replaces part of those 100 units of clinker with 50 parts of GGBFS. If you take one part of that and bring in geopolymer, it uses GGBFS and removes it from the equation for the OPC.

So basically we are staying in the same usage of clinker and GGBFS. What I think is much more efficient — or promising — is that we find the application that can bring new raw materials into the equation. Then the OPC production can use the GGBFS, and geopolymer brings in, let's say, a few units of steel slag. And then those few units of steel slag replace part of the OPC or the clinker, and the cement industry still gets to use the GGBFS. That's the way in the big picture — you can really see that we are reducing the use of the highest-impact raw materials.

Also, when we think about the efficiency of material usage: when you make, let's say, 1 cubic metre with OPC, the binder usage is usually much more efficient than in geopolymers. So if you want to make a concrete with 30 MPa of strength, you can use a clinker amount of 300 kilos — that's clinker and blast furnace slag. But to get to the same performance with geopolymer, you might have to use 350 or 400 kilos of binder. So that's also what you need to calculate. What is the most efficient use of GGBFS? And in my opinion, it might not always be geopolymer concrete.

Sam Meeuwis – 26:44 Yeah, I think that's a very valid point, because all the different sources you need in concrete are ones that actually have an impact on the environmental impact overall. So if you want to look at concrete, it's more than only the binder. Therefore a more holistic approach to this seems logical — but then if you do that at too large a scale, you also kind of get lost in the amplitude of possibilities. So I was wondering: do you think that maybe we should look at — for instance, if we have 100 different types of precursors that can be used for geopolymers — should we list the 15 most prominent ones? And really focus our energy and our academic research and field implementations on those, and say: okay, then we have 15 recipes which we can tweak. But those are the 15 that have shown to be truly the best. Is that a better path forward than what we're doing now, where everybody is doing whatever they want — and then some of the research is not that useful, actually?

Autio, Mika – 28:20 Yeah. I mean, if we want to make the biggest impact at large scale in the future, it is definitely worth finding out if there are new raw materials that we can use. So I know that in geopolymers, GGBFS is the king — that is the most efficient, the best raw material available, especially in Europe. One big thing that can be used in the future is definitely kaolinite clay-based geopolymer. There I can foresee a brighter future than in GGBFS-based geopolymer, since clays can be a very abundant material source in the world, of course. In Europe, there is the problem that the clay types we have here have very low kaolinite content, and kaolinite clay minerals are found worldwide. But there are some sources in Europe as well that can be considered efficient raw materials for concrete, and also possibly for geopolymers. So yeah, in my opinion the biggest impact — or biggest promise — could be bringing these new raw materials into play.

Sam Meeuwis – 29:51 So then what do you think needs to change to make sure they get into play? Is that something which will happen just because of supply and demand in the market, or do you think there needs to be an active role somewhere in governance to promote that?

Autio, Mika – 30:18 Yeah, it is partly a question of supply and demand. For example, for kaolinite clays there's not a big market yet — there's only a little bit of production out there. That will be rising and increasing the amount of raw material available in the future, and once we have more of it, I'm sure that more people will try to make better products out of it.

One thing that is driving the development of new raw materials is the steel and iron industry. They are changing their processes — in the future, and already now, moving more from traditional blast furnaces to electric arc furnaces. And they have huge new material streams which are waste streams that they cannot yet quite use. GGBFS is already a valuable material that can be sold, but these new slags will remain waste for them. Most of the steel slags, copper slags or other metal slags currently cannot be sold, and if it's a waste, it can be really expensive for them to get rid of. If they would, for example, partner up with different technology companies to develop technologies to use these slags as raw material for geopolymer or cement, that could fix their huge waste-based problem.

Sam Meeuwis – 32:09 Yeah, I think that's also one of the key drivers in this research — that you are actually using waste-based materials. So on paper it should also have a very big market improvement. Because you're using waste sources, and that's always economically beneficial — it should be better. And it should be your incentive in all markets to actually reuse it.

Since we're talking about waste and reusing it now: in my research I'm also looking at reusing building demolition waste as aggregates. What do you think about that? Like closing the loop in the built environment — do you see big problems with geopolymers? Or with concrete and reusing that?

Autio, Mika – 33:13 No, you can reuse it — like using recycled aggregates, it's a very good thing to do. There are certain things you need to know about how to process it — how to turn demolition waste into usable aggregates for concrete. But once you know how to do it, it is locally a very good thing to do.

Of course, there are challenges with recycled aggregates in concrete. For example: when you have demolition waste and you crush it, you get a lot of fine concrete dust. And that is problematic in concrete mixes. So you would either have to separate it so that you only use the coarse parts, or you really need to process that fine part into a filler or something like that. And that processing can be challenging. And all of that, again, comes back to the cost side of things.

It really depends on what market we are working in. In the Netherlands, the use of concrete demolition waste for aggregates is financially and environmentally much easier or better, because the Netherlands doesn't have that many natural resources to use. There is already some legislation in place that makes that side of things more beneficial.

So comparatively — if you have natural aggregates, usually the quality is better. And in other markets — I'm not actually quite sure what the price difference is in the Netherlands — the natural aggregates are actually still cheaper than processed concrete demolition waste. When I was working in Finland, we were doing testing and figuring out how to use recycled concrete aggregates in concrete. We found out that because in Finland we have a virtually unlimited amount of natural aggregates available, that are very high quality, if we went to use recycled aggregates it would cost us more and would also reduce our quality. You don't necessarily have to do much to your mix designs if you do it. But without processing it properly, actually using recycled concrete aggregate might make your concrete weaker — which would then cause you to use more binder, and that wouldn't be sensible.

Sam Meeuwis – 36:31 So you have to keep the balance always in the right spot. Since I was at a recycling facility on Tuesday, they actually told me — because Renewi has a recycling plant that uses water to separate the ultra-fine particles — they claim that they are not yet at the capacity of what their machines can actually do. Because the demand is not there yet. They can separate much, much more broadly, much finer, much better, more different types of stony materials. From the crushed aggregates I saw there, these recycled products were actually very high quality products. But the only thing they couldn't yet find a new use for was the fine particle paste. Do you think — because you said earlier that there are companies researching activating stony materials — that maybe there will be a future where we can actually use that fraction? Activate it again and use it in the concrete?

Autio, Mika – 38:02 Yes, there is research going on about this. There are some very promising results on the use of this. Basically, there are methods you can use to activate the cement fines and other ultra-fine particles. There is some promise to it. I don't think it will ever be like a highly demanded product. But if you are thinking about using it, maybe it can replace 5 to 10% of cement in your mix design without reducing the quality of your concrete or cement.

And 5 or 10% of the world cement industry's input into cement production is already a huge amount of material. So even if it's not as good as GGBFS — where you can go up to 70% replacement — or in geopolymers even 100% replacement — even a 5 or 10% at large scales is a lot.

Sam Meeuwis – 39:23 So another part which I hear quite often in the recycling sector is that they are concerned about the quality of their product — whether they can guarantee it, if we are in a transition period.

So we're transitioning to new types of concrete, new types of resources used, and they all end up in the recycling facility at the end of their life. Do you think that might become a problem when we start implementing geopolymers — that they get recycled in the end and might end up in normal concretes, and vice versa? Do you think that's a big problem in the future?

Autio, Mika – 40:21 It might be. It is definitely something that we need to understand a little bit better.

I'm not a super expert on the recycling industry. I was also working a little bit with my colleagues on that in Finland, and there the legislation about testing of recycled concrete and recycled aggregates was a challenge. For example, we noticed the leaching of materials from recycled geopolymer-type concretes. The recycling company has to test their recycled concrete, and if certain leaching values go over certain limits, it becomes much more difficult to recycle. And if geopolymers are more prone to this type of leaching, it definitely can be a problem. It is something that we need to understand a little bit better. Currently, at this time I don't know how recyclable geopolymer concretes are, and I think that's something that we need to figure out a little bit better.

Another thing that can be a challenge — whenever we are increasing the recycling rate of our products — is the inconsistency of the quality of the raw materials whenever we have a batch of concrete. If its quality is different depending on where it comes from, there might be more impurities, there might be different types of concrete used, and the type of aggregates gained through recycling are different. In contrast, in the construction industry it is very important for us that the quality of the raw materials we are using is very consistent — because if we get a jump of 10% or a drop of 10% in quality, it can be quite devastating to our mix designs. We always try to be efficient in our cement use, so there's not necessarily always a huge margin in the mix without impacting the strength. And if one of our raw materials fluctuates from one week to another, it breaks that margin of quality that we are producing. It's a big problem.

I can quickly show you this — [diagram of quality fluctuation in Finland of resource materials] — this problem is already sometimes present in the quality of GGBFS, since GGBFS comes from the steel manufacturer and they do not optimise their process to keep the quality of GGBFS consistent. So over time it goes up and down, and we can see that quality change affecting the strength of our concretes. This graph — this one here — is the strength graph from GGBFS from Finland. This is the activity index.

So basically, you can see that between different days of production, the activity index can go from 90% to 120%. In OPC, this effect is manageable since you might use 30% GGBFS — from 30% you might get a little bit of effect on strength development. But what happens when you have a binder of 100% GGBFS and your geopolymer concrete strength is changing from one batch to another? The quality goes from 90% to 120%, or opposite — from 120% to 90%. If you make your mix design when you have the high quality slag and then produce again in the next batch where you get 90% quality instead of the 120% you had before, then the effect is even larger. What's the point at which you have to change your mix design? How do you know when you have to change your mix? The challenge when you are using waste materials is to make your product always the same quality, even though the quality of the raw materials can sometimes be very inconsistent.

Sam Meeuwis – 45:23 Should there then be a second processing step for these waste materials, in your opinion, to guarantee their quality?

Autio, Mika – 45:38 Definitely there needs to be testing of the quality. I don't know in geopolymers how much this type of quality change actually affects things. Is it a little bit more forgiving? I don't know — because the test I showed you is done with cement and slag. The results from this test are basically from the concrete producer. They get these results from the batch that they make, they test the concrete afterwards, and then they know how much it differed from 100% clinker, and then they know the reactivity of the GGBFS. Then they know, for instance, if they have to make it a bit stronger. But for geopolymer concrete you'd have to test beforehand. I guess they should then figure out what's the best way to test the quality of your raw material before using it. It's really difficult, because this kind of test might take a lot of time — and I simply do not know how best to do it.

Sam Meeuwis – 46:54 Yeah, I think that's also one of the concerns of many of the new market players. The question of quality consistency is a big, big question mark. Also with Sonja Fennis of Rijkswaterstaat — I just interviewed her. They say it's very difficult for us because our standards are so much higher than in normal build environments. And then even a few percent difference could be detrimental in the long term, because they actually develop projects for 100-plus years. And if you have a 1% difference, it might impact your longevity by way more than 1%. So it all trickles down.

Do you think there's something to be said for making it — instead of a local approach — a broader approach, so you can actually have all the resources to manage all these things and get a very good, consistent, qualitative product? Or do you say: no, you should adopt a very local approach for this problem and make sure you have it at the local scale, where you have very concise measurements of all the different flows, so you know exactly where they come from and can therefore guarantee the quality?

Autio, Mika – 48:52 It's really difficult to say — it is a very complex matter, since again, there are so many different ways you can make geopolymer concretes, and there is still so much more that we need to understand. I think if we are thinking about standardisation — on the local level or European level — maybe the approach and usage of waste streams needs to be a little bit different than in the production of cement. I don't know what would be the best way to do it.

Usually, probably this would have to start on the local level, and once we find out the best way to do it, maybe then it can be translated into European standardisation.

Sam Meeuwis – 50:07 To sort of finalise the interview: what is, in your opinion, what actually needs to change or needs to happen to make sure that we get to durable concretes in the future? And how do you see the chances for geopolymer concretes in that future?

Autio, Mika – 50:55 To be realistic and a little bit cynical: money drives things. There needs to be legislation that makes low-carbon concretes or geopolymers a more and more attractive option than it already is. The carbon tax, for example, is driving the price of OPC up — and that is going to make geopolymer concrete a financially more attractive option in the future. That is number one.

Number two: we need to have either local or European level standardisation for geopolymer concretes. In some countries they already have some norms and standards in place that allow the use of geopolymer. Once there are more of these standards and guidelines on how to do it, and people understand how to do it, there will be more knowledge and information in the field. Once we have more information we can make more educated choices in selecting our raw materials for different projects. I think those are the main things. Of course the technology needs to still go and develop further and further — but once there is more desire in the field to use geopolymers, that will naturally come.

Sam Meeuwis – 52:53 I think that for a material to prove it's worthy of the transition, it should prove itself. And that shouldn't be driven by a large amount of tax benefits and such. Because in the end, you should be in search of the best solution for the problem, and that should always be the engineering case. And if it's not, then it's not that solution — and that is also a possibility. And I think that for some instances within the Netherlands, again there's something to say for: yes, this is the way to go — and for some instances and some raw resources, it is simply not doable in the Netherlands.

Autio, Mika – 57:57 *(about the diagram)* I would assume that similar kinds of quality changes are very common across different GGBFS sources as well. So this is testing the activity index of GGBFS. Basically, the test they do is: they take 75% of CEM1 and 25% of GGBFS and compare it to 100% CEM1, and from that difference in strength they get the activity index.

Diagram: Activity index for GGBFS — sourced from Mika Autio, CRH, Finnsementti

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Formatted by Claude 4.6 Sonnet — interview conducted in English.

Site Visit: Renewi Building Waste Separation Plant (2025)

A site visit to Renewi's Building Waste Separation Plant provided first-hand insight into current demolition waste processing logistics in the Netherlands. Key observations are integrated in Section 3.2. Photographic documentation from the visit is to be added here.



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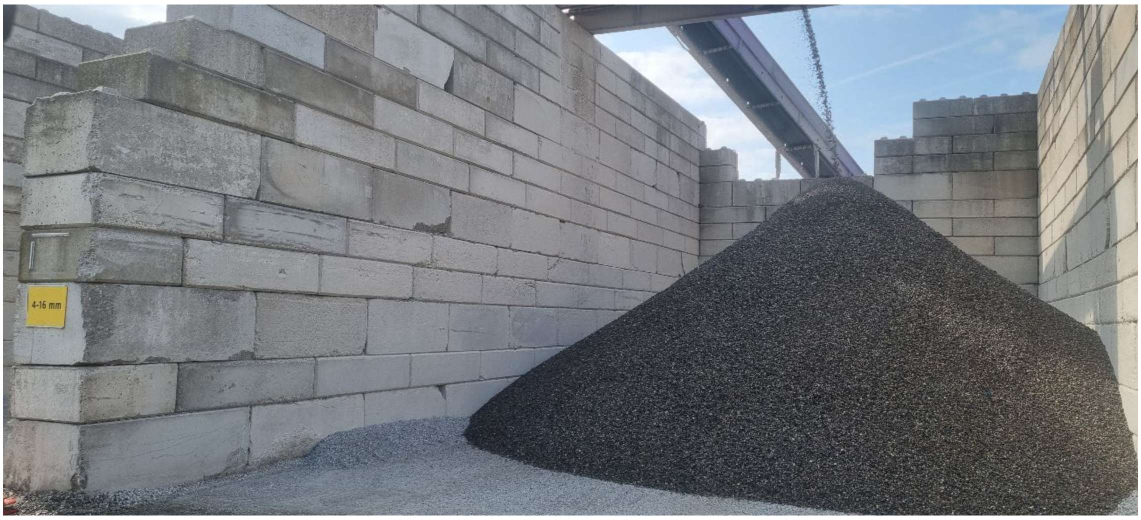
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C. RILEM TC 294-MPA Training Course – Diploma

The author completed the RILEM TC 294-MPA one-week intensive training course on alkali-activated materials in Delft in 2025, earning 4 ECTs and receiving an official course diploma. The course covered fresh properties, mechanical performance, shrinkage, creep, bond behaviour, fibre reinforcement, mix design, non-conventional precursors, and conventional precursors and activators, delivered by leading international researchers in the field. Much of the knowledge and data referenced in this paper under the 2025 lecture citations originates from this course; where cited research has not yet been published in peer-reviewed form, reference is made to the lecture contribution directly.


van den Berg