



Ministry of Environment
of Denmark
Environmental
Protection Agency

WARM **Industrial Scale** **Production of** **Paving Stones** **from** **Waste and Recycled** **Materials**

MUDP

October 2026

Publisher: The Danish Environmental Protection Agency

Editors:

Stuart Clyens, STEKKER

Christian Løjtved, ECC

(hereafter jointly referred to as "CC")

ISBN: 978-87-7564-167-3

The Danish Environmental Protection Agency publishes reports and papers about research and development projects within the environmental sector, financed by the Agency. The contents of this publication do not necessarily represent the official views of the Danish Environmental Protection Agency. By publishing this report, the Danish Environmental Protection Agency expresses that the content represents an important contribution to the related discourse on Danish environmental policy.

Sources must be acknowledged

Miljøteknologisk Udviklings- og Demonstrationsprogram

Projektet, som er beskrevet i denne rapport, er støttet af Miljøteknologisk Udviklings- og Demonstrationsprogram (MUDP) under Miljøministeriet, der støtter udvikling, test og demonstration af miljøteknologi.

MUDP investerer i udvikling af fremtidens miljøteknologi til gavn for klima og miljø i Danmark og globalt, samtidig med at dansk vækst og beskæftigelse styrkes. Programmet understøtter dels den bredere miljødagsorden, herunder rent vand, ren luft og sikker kemi, men understøtter også regeringens målsætninger inden for klima, biodiversitet og cirkulær økonomi.

Det er MUDP's bestyrelse, som beslutter, hvilke projekter der skal modtage tilskud. Bestyrelsen betjenes af MUDP-sekretariatet i Miljøstyrelsen.

MUDP-sekretariatet i Miljøstyrelsen

Lerchesgade 35, 5000 Odense | Tlf. +45 72 54 40 00

Mail: ecoinnovation@mst.dk

[MUDP's hjemmeside](#)

Denne slutrapport er godkendt af MUDP, men det er alene rapportens forfatter/projektlederen, som er ansvarlige for indholdet. Rapporten må citeres med kildeangivelse.

Table of contents

1.	EXECUTIVE SUMMARY	5
1.1	Project Summary	6
1.2	Overall Project Conclusion	6
1.3	Derived effects - Structural Decarbonisation and Replication Potential	7
1.4	Perspective – BioFreeze - Targeted Performance Refinement	7
2.	Introduction and Industrial Context	8
3.	Project structure – Objectives and Industrial Validation Strategy	9
4.	Technological Platform and Material Strategy	11
4.1	Reducing clinker content of conventional cement	11
4.2	Bio-based ash as a source of aluminosilicates	12
4.3	Crushed concrete	12
4.4	Waste Glass-Based Binder for Concrete	13
4.5	Flint sands in low clinker concretes	14
4.6	Advanced design of experiment (DOE) and response surface methodologies	15
4.7	Elimination of biocides	16
5.	Performance, Standards and Industrial Robustness	17
6.	Industrial Implementation and Market Readiness	21
7.	Demonstration, Market Integration and Replication Potential	24
8.	Environmental Framework and Structural Impact	27
9.	Dissemination of project results	29
9.1	Overall Impact of Dissemination Activities	30

1. EXECUTIVE SUMMARY

The WARM project demonstrates that significant and scalable CO₂ reductions in concrete paving products are already achievable today through industrial implementation of a new binder technology platform.

At the core of the project lies the TriαSi™ platform, a CC-developed activated aluminosilicate technology that replaces a significant share of clinker as the primary binding mechanism in concrete. Rather than relying on a single formulation, the platform enables the use of a wide range of mix designs based on diverse aluminosilicate sources, including bio-based ash, recycled materials and industrial by-products. This flexibility is a key enabler for both environmental performance and industrial scalability.

WARM builds directly on the earlier RELO project, where the technology was developed and validated at laboratory scale. As an MUDP-supported lighthouse project, WARM has successfully translated this technology into full-scale industrial production. The TriαSi platform has been implemented in an operational dry-pressed production line, demonstrating stable manufacturing, DS/EN compliance and repeatable product quality under real production conditions.

The project confirms that CO₂ reductions of 40–57% (A1–A3) can be achieved for paving products, without compromising performance, durability or cost competitiveness. For high-volume products such as paving stones, this represents a substantial societal impact. If implemented broadly, the technology has the potential to reduce CO₂ emissions by hundreds of thousands of tonnes annually, while positioning Denmark as a frontrunner in low-carbon concrete solutions. Of equal importance, the project shows that environmental performance and economic competitiveness are not mutually exclusive, enabling immediate industrial adoption without structural cost barriers.

Real-world implementation has been demonstrated through multiple projects, including the installation of paved areas in Næstved and Fælledby, confirming that the technology is not only technically viable but fully market-ready.

Beyond CO₂ reduction, WARM contributes to circular economy principles by enabling high utilisation of recycled materials including crushed concrete. This reduces dependency on virgin aggregates (e.g. gravel), minimises waste streams, lowers transport needs and enables near zero-waste production systems. The project also demonstrates the successful use of flint sand aggregates, expanding the usable raw material base.

The development process has further led to CC-technology spin-offs, including a novel approach to accelerating early strength through nano-scale silicate seeding. This innovation addresses one of the key challenges in low-clinker systems and strengthens the commercial viability of the platform.

The WARM project has met all its objectives and represents a complete innovation pathway, from concept and laboratory validation to full-scale industrial production and real-world deployment. The results demonstrate that the paving industry already has the technological foundation to meet, and exceed, previously defined 2030 targets of 50% CO₂ reduction. With leading edge products now approaching a 60% reduction, the platform is well positioned to contribute to the now elevated 70% industry ambition.

In conclusion, WARM establishes the TriαSi platform as a scalable, industrially validated and economically viable pathway for low-carbon concrete, with clear potential for expansion into additional concrete product categories and broader international deployment.

1.1 Project Summary

The WARM project has demonstrated that substantial CO₂ reductions in concrete paving products can be achieved within existing industrial production systems. More importantly, it has shown that such reductions can be realised without compromising regulatory compliance, production stability or market competitiveness.

The project does not represent a laboratory curiosity or an isolated pilot installation. It represents the industrial validation of the TriαSi platform under real operating conditions, integrated into a functioning dry-cast production environment and verified through completed EPD documentation.

At the same time, the project has provided a realistic understanding of the technological boundaries of the current platform.

While compliance with DS/EN 1338 and DS/EN 1339 has been achieved and freeze-thaw resistance under standard exposure conditions has been validated, performance under saline freeze-thaw exposure remains an optimisation area. This is not a regulatory deficiency, but a technical performance frontier that reflects the different pore chemistry and reaction mechanisms of aluminosilicate-based systems compared to high-clinker OPC formulations.

1.2 Overall Project Conclusion

The WARM project has successfully translated the TriαSi platform from laboratory optimisation to full-scale industrial production.

It has demonstrated:

- Verified CO₂ reductions of 40-57% within A1-A3 system boundaries
- Compliance with DS/EN 1338 and DS/EN 1339 under industrial conditions
- Stable and repeatable industrial production at the Hedehusene lighthouse facility
- Completed and independently reviewed EPD documentation
- Real-world installation in municipal and urban development projects
- Based on a conservative average of 40% CO₂ reductions across all IBF's production facilities, the resulting CO₂ savings would be approximately 52,000 tons CO₂/annum corresponding to 28,000,000 cubic metres of CO₂/annum.

Crucially, the project confirms that deep emission reductions in concrete paving products can be achieved within existing industrial systems through structured material substitution and process control.

The lighthouse implementation in Hedehusene shows that sustainable material innovation can transition from research-driven development to standard industrial practice. The TriαSi platform has been validated not only technically, but operationally and commercially.

WARM therefore represents a practical pathway for the paving industry to contribute to national climate objectives while maintaining competitiveness and regulatory compliance.

1.3 Derived effects - Structural Decarbonisation and Replication Potential

Concrete paving stones represent a high-volume product category with significant cumulative climate impact. Even moderate per-unit reductions translate into substantial aggregate emission savings.

The WARM project demonstrates that reductions of 40-57% (A1-A3) are achievable without radical restructuring of production infrastructure. Because the required modifications are technically manageable and economically proportionate, replication across comparable facilities is feasible.

If adopted more broadly within the paving sector, the structural decarbonisation potential becomes significant. The reduction mechanism is intrinsic to the material system and therefore scalable in proportion to production volume.

The project thus provides not only a technological proof-of-concept, but an implementation model for industrial transition.

1.4 Perspective – BioFreeze - Targeted Performance Refinement

The BioFreeze project, which will run from April 2026-March 2028, will build directly on the TriαSi technological platform validated throughout the WARM project. Its objective is not to re-define the binder chemistry, but to refine specific durability characteristics within the existing TriαSi platform.

The focus areas include:

- Improved resistance under saline freeze-thaw conditions
- Microstructural optimisation of pore distribution
- Development of additive systems tailored specifically for aluminosilicates

By targeting well-defined performance parameters rather than revisiting fundamental chemistry, BioFreeze represents a continuation of a validated industrial pathway rather than a reset.

The existence of a functioning lighthouse facility and completed environmental documentation significantly reduces the development risk for follow-up optimisation. BioFreeze therefore builds upon an industrially proven foundation rather than a theoretical concept.

Beskriv de effekter I forventer at projektets resultat(er) vil kunne afstedkomme for samfundet og eventuelt forskellige typer aktører der ikke har deltaget i projektet. Hvad kan det få af betydning, hvis projektets løsning/resultat(er) implementeres/markedsføres i årene efter projektafslutning? Hvilke effekter kan dette projekt potentielt have fx på teknologiudvikling eller udvikling inden for regulering?

2. Introduction and Industrial Context

The construction sector is currently undergoing major structural transformation driven by climate legislation, resource constraints and increasing documentation requirements. Simultaneously, concrete remains indispensable for infrastructure and urban development, yet the production of Ordinary Portland Cement (OPC), used across all concrete applications, accounts for approximately 8% of global anthropogenic CO₂ emissions.

Within high-volume product categories such as concrete paving stones and paving flags, even moderate CO₂ reductions per unit can translate into significant cumulative emission savings. However, meaningful reduction requires intervention at the material level, where clinker content constitutes the dominant emission driver.

The WARM project was initiated to demonstrate that substantial CO₂ reductions can be achieved through structural modification of the binding mechanism in concrete products - not through marginal efficiency gains, but through substitution of clinker as the primary binder phase.

WARM builds directly upon the earlier MUDP-supported RELO project in which hybrid binder systems based on alkali-activated aluminosilicates were developed and tested at laboratory scale. The RELO project demonstrated:

- Compressive strengths exceeding 35 MPa
- Bending strengths exceeding 5 MPa
- pH levels comparable to conventional concrete
- Satisfactory freeze-thaw resistance under standard exposure
- Significant reduction in global warming potential

These results confirmed technical feasibility. However, laboratory validation does not automatically guarantee industrial robustness. Reaction kinetics, moisture tolerance, compaction behaviour and production variability can differ substantially under full-scale manufacturing conditions.

WARM was therefore conceived as the industrial realisation of the technological foundation established in RELO. The objective was to transition from a laboratory proof-of-concept level to a stable, compliant and economically viable industrial production.

For the purpose of this report, ECC and STEKKER are referred to as CC. It is these two companies that developed the underlying aluminosilicate-based binder technology (known as TriqSi™) which forms the basis of the WARM project.

The core technological platform applied in WARM is the so called TriqSi™ platform in which alkali-activated aluminosilicate materials are employed as the binding mechanism in concrete products. The invention is not limited to a specific mix design, but encompasses the application of this binding principle across formulations that fall within its natural technical scope. Within the scope of this report, this technology is referred to as the TriqSi platform - an alkali activated aluminosilicate platform redefining low-carbon construction.

While the binder technology and mix design optimisation were developed by CC, IBF, as industrial partner and owner of the lighthouse production facility in Hedehusene, implemented the physical plant modifications and validated the system under full-scale industrial production conditions. WARM therefore represents the transition from material innovation to industrial implementation.

3. Project structure – Objectives and Industrial Validation Strategy

From the outset, WARM was structured as a combined development and full-scale demonstration project (UDV + DMF). More specifically, WARM functions as a lighthouse project, with the primary objective of demonstrating that a technology developed at laboratory scale in the preceding RELO project, resulting in the TriSi platform, can be successfully implemented in full-scale industrial production.

To clarify the relationship between the project, the underlying technology and the resulting product categories, the overall structure is illustrated in FIGURE 1.

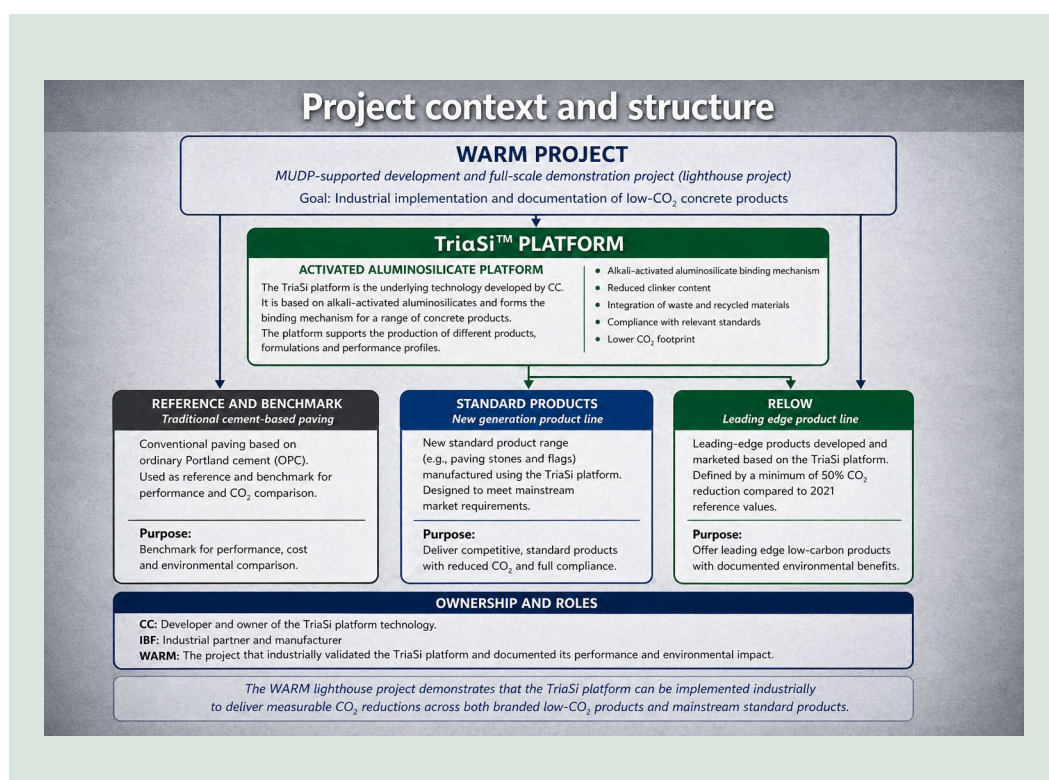


FIGURE 1. Overview of the WARM lighthouse project, the TriSi™ platform and product categories.

As illustrated, WARM is a lighthouse project focusing on industrial validation. The WARM project builds directly on the outcomes of the RELO project, where the core technology was originally developed and matured at laboratory scale. The development work carried out under RELO resulted in the establishment of the TriSi platform, which forms the technological foundation for all subsequent product implementations.

Under the TriαSi platform, two distinct product categories are defined.

First, the standard product range represents the next-generation mainstream products. These are designed to meet conventional market requirements in terms of performance, cost and compliance, while achieving reduced CO₂ emissions through the application of the platform.

Second, the RELOW product line represents the leading-edge application of the platform. These products are specifically designed to target maximum environmental performance and are defined by a minimum CO₂ reduction of 50% compared to conventional reference products.

Conventional, cement-based products were also a part of the WARM project and were used as a reference and benchmark. These products are not part of the TriαSi platform, but serve as a baseline for comparison in terms of performance, cost and environmental impact.

One of the main objectives of the WARM project was not only to demonstrate a low-carbon niche solution, but to validate that a single underlying technology platform can support both mainstream products and high-performance low-carbon products within existing industrial production systems.

The project was guided by five integrated objectives.

First, to implement the TriαSi platform in a functioning dry-cast paving production facility. This required integration into existing mixing, compaction and curing systems without fundamental redesign of the production infrastructure.

Second, to demonstrate measurable CO₂ reductions relative to a documented baseline of 18.7 kg CO₂/m² for a conventional 7 cm paving stone (2021 reference, A1-A3). The environmental objective was defined quantitatively and verified through EPD documentation authored by an independent third party who did not participate in the project.

Third, to ensure full compliance with DS/EN 1338 (concrete paving blocks) and DS/EN 1339 (concrete paving flags). Mechanical performance, dimensional stability and durability all tested under industrial production conditions.

Fourth, to optimise binder composition with respect to strength development, durability and cost. Particular attention was given to binder formulations suitable for industrial use, with early-age strength development and those employing waste-derived and recycled materials.

Fifth, to subject environmental documentation to independent review, including verification of value chains, allocation principles and production data consistency.

The lighthouse facility in Hedehusene functioned as the central implementation platform. Here, laboratory-optimised formulations were translated into industrial production logic, enabling validation of scaling behaviour and operational stability.

The structure of WARM therefore combined material science, process engineering and environmental verification within a single integrated framework.

4. Technological Platform and Material Strategy

4.1 Reducing clinker content of conventional cement

At the centre of WARM lies a hybrid binder system based on alkali-activated aluminosilicates. Rather than relying predominantly on clinker hydration, the system activates aluminium- and silicon-rich materials under alkaline conditions, forming a hardened binder network with mechanical characteristics comparable to conventional cement systems.

The objective was not to abandon cement entirely, but to substantially reduce clinker content while maintaining regulatory compliance and industrial workability.

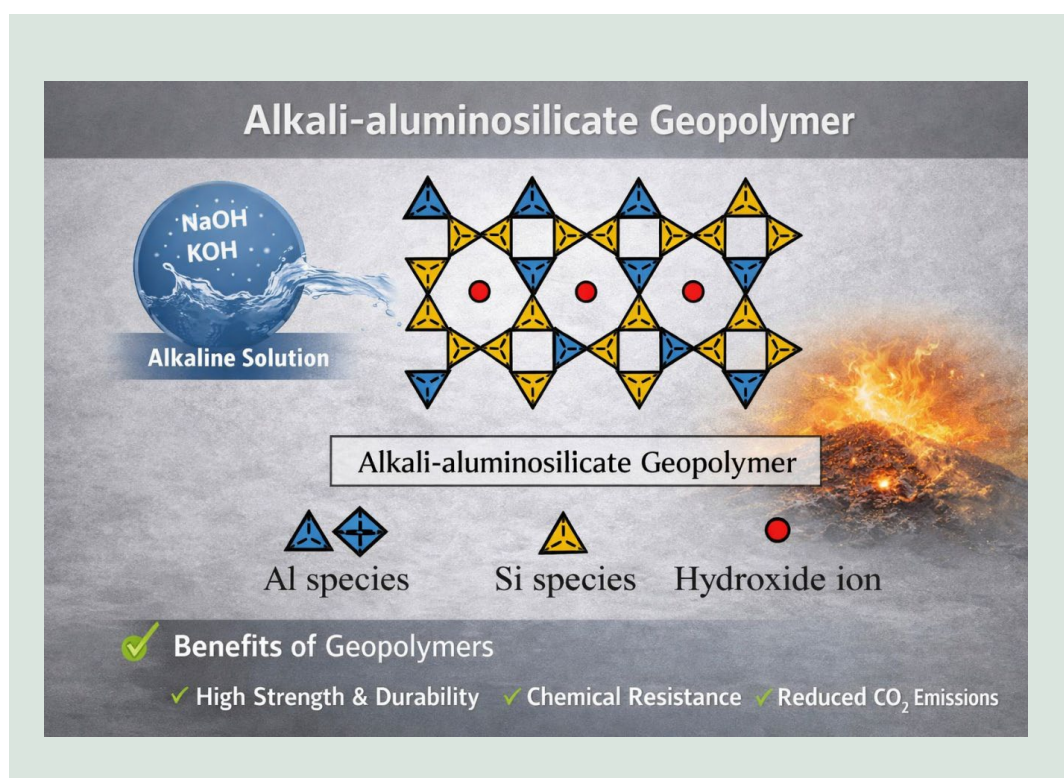


FIGURE 2. Hybrid aluminosilicate-based binder concept.

Schematic representation of the CC-developed binding mechanism based on alkali-activated aluminosilicate.

The WARM project builds on an earlier MUDP supported project RELO which demonstrated that concretes with a 40-50% lower CO₂ footprint could be manufactured at laboratory scale through the alkali activation of materials (TriαSi platform) containing significant amounts of aluminosilicates.

The WARM project was established to not only demonstrate that the TriαSi platform technology could be translated from a laboratory to an industrial scale but also to investigate the use of recycled materials such as bio-based ash, waste glass and crushed concrete. Another project aim was to investigate the possibility of substituting the quartz sands, used in conventional concrete manufacture, with flint sands, which are widely available but not ideal for use in conventional OPC concrete.

4.2 Bio-based ash as a source of aluminosilicates

Bio-based ashes, produced by combusting e.g. wood chips, straw pellets mixed with coal dust, are available from certain Danish power plants. Normally, burning wood chips or straw pellets alone would only produce ashes that are rich in silica but contain low amounts of aluminium which limits their use as a source for generating aluminosilicates. However, coal does contain significant amounts of aluminium in the form of aluminium oxide, so that, when mixed with e.g. wood pellets and burned, the resulting ash contains significant amounts of aluminosilicates.

Currently bio-based ash sourced from Danish power stations is approved for use as a filler in concrete mixtures. In its “as received” state the ash only exhibits a low pozzolanic activity. However, tests carried out in the WARM project have shown that, when combined with other suitable materials, the bio-based ash can be used, not only as filler, but as a binder adding significant strength to concretes to which it is added.

After a great deal of experimentation, a binder was eventually developed that enabled concrete to be manufactured with a minimum 50% lower CO₂ footprint. The material composition of this binder enabled the manufacture of concretes that had comparable mechanical properties to OPC based concretes but significantly less expensive.

4.3 Crushed concrete

The integration of crushed concrete represents an important contribution to the circular material strategy within the WARM project. While the primary CO₂ reductions are achieved through the binder system in the TriαSi platform, the use of recycled concrete addresses a different but equally important dimension: the reduction of reliance on virgin raw materials.



FIGURE 3. Material flows utilised in the WARM project.

Illustration of circular material integration supporting reduced clinker consumption and improved resource efficiency.

Within WARM, it has been demonstrated that significant amounts of crushed concrete can be used with the TriSi™ platform without compromising production stability or product performance. Demolished or rejected concrete products are crushed, cleaned and fractionated into defined particle sizes, after which they are directly reintroduced into the production of new paving products.

The use of recycled concrete does not in itself lead to a substantial reduction in CO₂ emissions in the A1-A3 phases. However, it delivers clear benefits in terms of resource efficiency and system optimisation. The approach reduces the demand for virgin aggregates such as gravel, which is expected to become an increasingly scarce resource in the future. At the same time, it minimises the need for external disposal, reduces transport requirements and enables near “zero-waste” production at the factory level.

A key observation from the project is that the technically feasible substitution level of crushed concrete is relatively high. In several cases, the limiting factor has not been technical performance, but rather the availability of suitable recycled material. This indicates that crushed concrete may, under certain conditions, shift from being a waste stream to becoming a constrained resource within the production system.

The integration of crushed concrete therefore complements the CO₂ reduction achieved through the TriSi platform by strengthening the overall resource efficiency and circularity of the production system.

4.4 Waste Glass-Based Binder for Concrete

Crushed waste glass, produced by Danish recycling plants, is normally cleaned and sold back to manufacturers of glassware (e.g. Holmegaard værk), however the crushing process presently produces approximately 2000 tons/annum of waste glass powder which is too fine for use in industry and is presently disposed of in landfill and/or exported resulting in further CO₂ emissions related to transport.

During the WARM project a large number of experiments were carried out to investigate ways in which waste glass powder could be used as part of a binder suitable for concrete manufacture. These experiments focused on basically mixing and dissolving the glass powder at temperatures of approximately 150-250°C and pressures of 1-1.5bar using different amounts of sodium hydroxide prills and a small amount of water.

The mixture of glass powder and sodium hydroxide was processed in a stainless-steel pressure vessel heated in a hot air oven. Numerous experiments were carried out to identify the experimental optimum which resulted in material which could be used as a hybrid binder system for concrete.

Many different formulations were tested and it was demonstrated that some of the resulting processed mixtures could be mixed with sand stone aggregates to produce concretes with compressive strengths of 30-40MPa, which is more than adequate for the manufacture of paving stones. However, the same tests also showed that, when mixed with aggregate and cured at room temperature, the hybrid binders did not result in a concrete achieving the same early strength as conventional concrete.

Unfortunately, this lack of early strength meant that the glass-based, hybrid binder could not be used for paving stone manufacture without increasing the curing temperature to 60°C. In IBF's case, this would have required a major redesign of IBF's curing facilities which presently operate at room temperature.

Attempts to increase the reactivity of the glass, by reducing the particle size, only met with limited success. It was shown that decreasing the glass particle size down to around 1 micron did

increase reactivity of the glass powder but it was found that the grinding process could only be successfully carried out using wet grinding which then resulted in a binder material that was too costly and too wet for paving stone production.

Simply using the fine glass powder as a filler was also explored. However, although there are 2000 tons/annum of glass powder available, in order to feed the glass powder into the concrete mixture, the construction of a silo, is required. Under the present economic climate, it was felt that cost-benefit of using glass powder merely as a filler would not justify the construction of an extra silo. However, this situation may change in the future if other filler materials become scarce.

One very positive spin-off identified by CC, was the realization that the very small glass particles, which are basically silicate, functioned as seeding locations in the binders being developed and that binder gel would grow around such particles. This led to further investigations to determine how even smaller silicate particles could be generated and added to the binders being developed, so that even more seeding locations could be created. These investigations eventually led to the development of a precipitation technique which allowed the creation of very large amounts of nano sized silicate particles that could be added directly to the binders being developed in the WARM project. The addition of these nano sized silicate particles had a dramatic effect on the development of early strength of concretes using these binders developed, increasing 7-day strength by more than 20%.

Although CC intend to continue with research into the use of fine glass powder as a binder in concrete production it is felt that, whilst the problems outlined above remain, hybrid binders containing waste glass for will not be employed for paving stone manufacture. However, as a result of attending the meetings and events described in Section 8, dealing with dissemination of the WARM results, the project partners have identified one Danish industrial concern which do employ warm curing of specialist concrete products. ECC and STEKKER are presently exploring the possibility of employing hybrid binders containing glass as well as other warm curing binders in this area.

4.5 Flint sands in low clinker concretes

The results described above all involved concrete formulations that employed stable quartz sands that do not react with the alkali environment generated by wet cement as much as flint sands.

Flint sands are microcrystalline and contain many defects and cracks which makes flint sands more soluble in the alkaline pore solutions within concrete. This can give rise to what is known as an alkali silicate reaction (ASR) which can lead to cracking of concretes containing flint sands. This is the main reason why the use of flint sands in concrete manufacture requires careful control.

It was known that TriSi family of binders do not react as strongly with flint sands as conventional OPC, and were therefore less likely to suffer the effects of ASR. Therefore, it was decided to test the idea of using one of the TriSi formulations to produce paving stones using a flint sand aggregate. These tests were successful and a total of 3.5 thousand square metres of Coloc paving stones were manufactured using flint sands as part of the aggregate system. However, it should be stated that these tests also showed that the time required for these flint sand based paving stones to cure to full strength was longer than the time required for paving stones manufactured using conventional marine and quarried quartz sands. Further research in this area is planned for the future.

4.6 Advanced design of experiment (DOE) and response surface methodologies

Concrete has a long history, dating back at least 2000 years. It therefore comes as a surprise to many that there is more to learn about concrete and that better versions of concrete can be found. However, it should be noted that the number of process variables involved in concrete manufacture are very large indeed and the number of experiments required to explore every combination of the process variables is of the order of several billions.

One of the ways to investigate such a large number of variables is through the use of mathematical methods which allow n-dimensional hyperspaces to be explored, where “n” is the number of variables. However, such spaces can only be represented and explored using computers equipped with software packages that allow the use of mathematical techniques dedicated to such a task.

Within the WARM project, CC have been using computational based DOE and response surface methodologies to try to identify optimal combinations (“sweet spots”) within hyperspaces that represent combinations of the variables related to concrete manufacture.

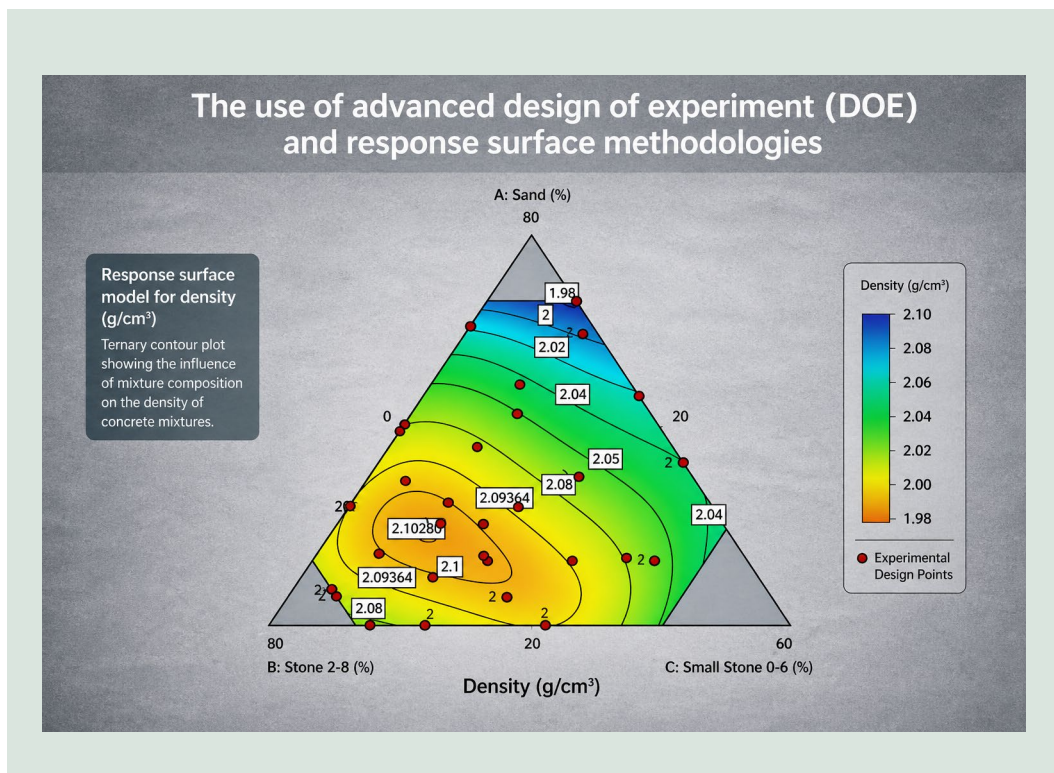


FIGURE 4. Example of response surface derived from DOE analysis.

Ternary representation of aggregate composition (sand, stone 2-8 mm, and small stone 0-6 mm) showing density as a function of composition. Contour lines indicate regions of increasing density.

As illustrated in FIGURE 4, the DOE approach allows complex multi-variable relationships to be visualised in a simplified form. In this example, a reduced parameter space (three aggregate fractions) is shown, where the resulting concrete density is mapped as a response surface. The contour plot highlights how specific combinations of aggregates lead to higher packing density.

This is of particular importance, as higher density is directly linked to improved mechanical strength and durability. The ability to identify these optimal regions enables targeted formulation development rather than relying on empirical iteration.

The techniques outlined above have made a major contribution to the successful development of a concrete that has mechanical properties comparable to conventional concrete but presently has up to a 57% lower CO₂ footprint.

4.7 Elimination of biocides

In addition, TriαSi formulations were designed to function without the need for superplasticizers which contain biocides, thereby reducing the possibility of harmful substances leaching into the environment.

The end result of all the work described above is not a single optimised product, but a scalable technological platform capable of continued refinement and industrial replication.

5. Performance, Standards and Industrial Robustness

The technical validation of the WARM project was not limited to laboratory performance metrics. The central objective was to demonstrate that the TriSi platform could deliver both mechanical compliance and operational stability under full-scale industrial conditions.

Environmental performance and mechanical validation were therefore carried out in parallel, ensuring that CO₂ reductions did not come at the expense of regulatory compliance or structural reliability.

The environmental baseline for comparison is a conventional 7 cm paving stone with a documented 2021 global warming potential of 18.7 kg CO₂/m² within A1-A3 system boundaries. Against this reference, the WARM project demonstrates verified reductions of approximately 57% for the RELOW product and more than 40% for the standard product range, based on documented 2025 production data.

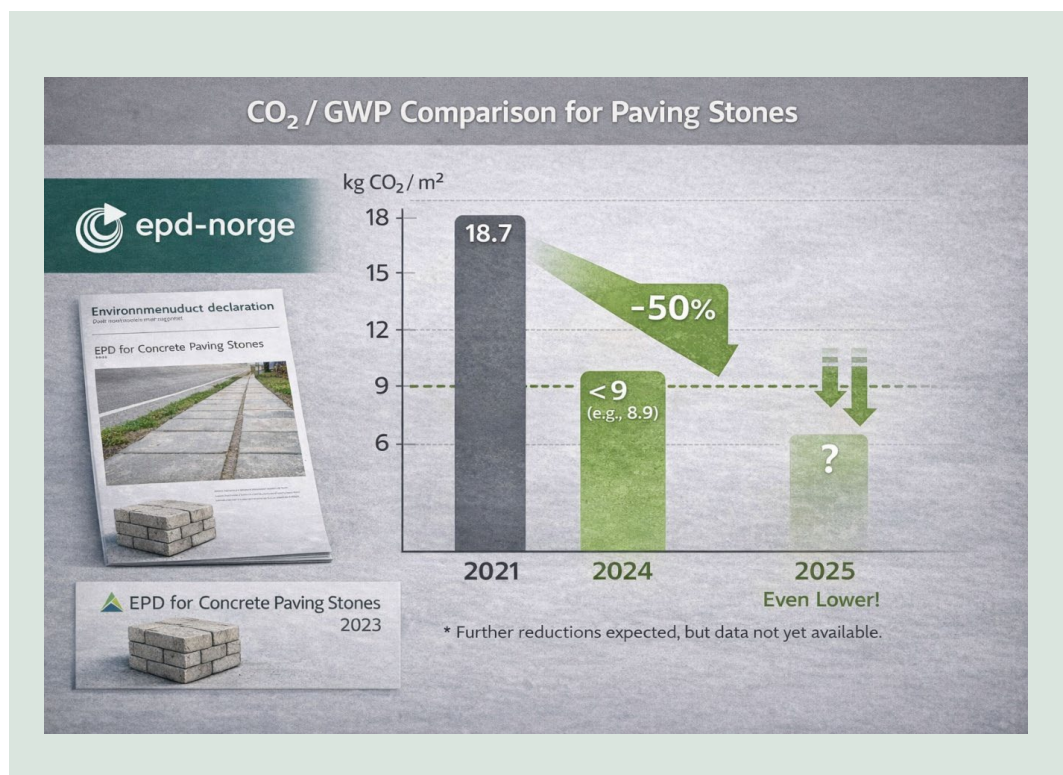


FIGURE 5. Comparison of global warming potential (GWP) for conventional paving stones and WARM products (2021 vs. 2024 values).

The figure illustrates structural emission reductions achieved through clinker substitution and binder optimisation.

These reductions are primarily driven by substitution of clinker through the TriSi platform. While energy efficiency and renewable electricity contribute to the overall performance, the

dominant reduction mechanism lies in material composition rather than downstream optimisation.

Mechanical validation was carried out in accordance with DS/EN 1338 and DS/EN 1339. Compliance with these standards under industrial production conditions was a decisive requirement for the project. The developed paving blocks and flags consistently met the required splitting tensile strength, bending strength, dimensional tolerances and surface integrity criteria.



FIGURE 6. Mechanical performance and compliance with DS/EN 1338 and DS/EN 1339. *Summary of mechanical validation confirming regulatory compliance under full-scale production.*

From a technical standpoint, the most critical phase was early-age performance. Alternative binder systems often exhibit different reaction kinetics compared to high-clinker OPC systems. During the initial optimisation phase, slightly higher sensitivity to water content and dosing precision was observed. This did not compromise compliance but required careful control of process parameters to ensure predictable behaviour.

The long-term strength development, for particular formulations, proved to be reproducible, confirming that the underlying reaction mechanisms of the TriSi platform are robust once the correct production parameters are established within industrial settings.

Durability performance under freeze-thaw exposure was evaluated according to DS/EN requirements. Under standard exposure conditions relevant to Nordic climates, the products demonstrated satisfactory resistance and maintained structural integrity.

Although compliance thresholds for freeze-thaw behaviour in a saline environment were met this area needs optimization work to further take into account the microstructural differences between high content-clinker systems and alkali activated aluminosilicates. However, the observed behaviour of the aluminosilicate formulations provides a defined development pathway rather than a structural limitation.

A critical validation step was documenting the transition from laboratory optimisation to industrial production. Absolute performance values varied slightly between laboratory and industrial scales, as expected due to equipment and compaction differences. However, performance trends remained consistent.

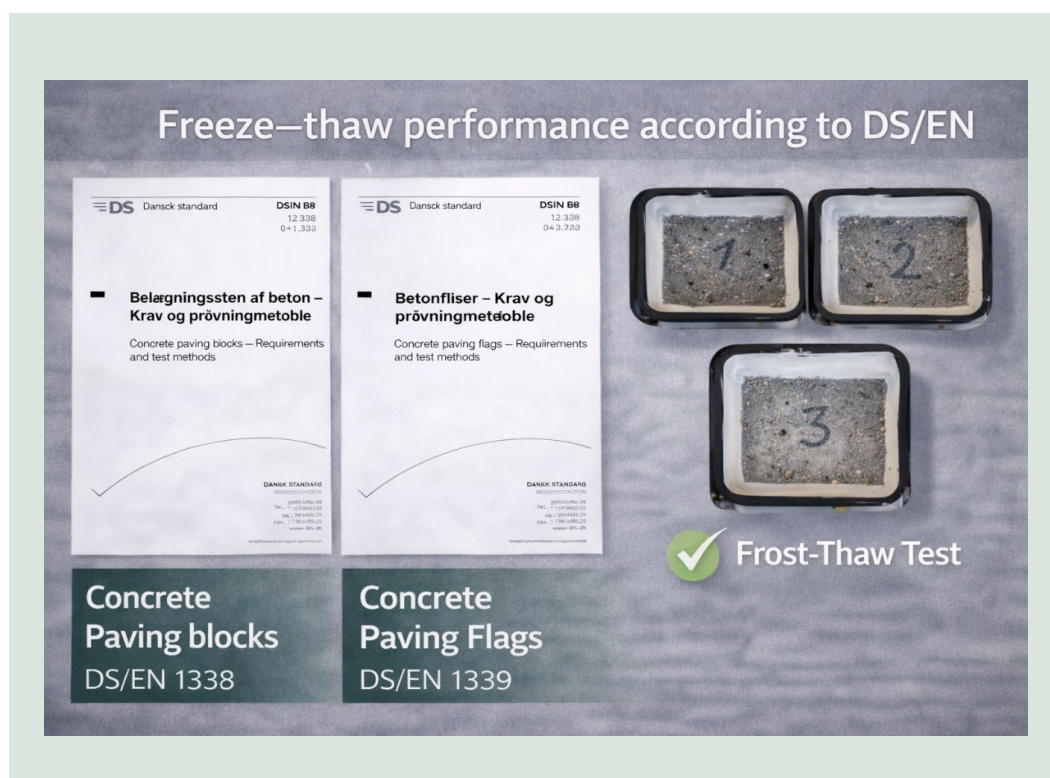


FIGURE 7. Freeze-thaw performance of WARM paving products.

Durability testing under cyclic freeze-thaw exposure confirming compliance with applicable standards.

The preservation of reaction behaviour across scales confirms that the TriαSi platform is scale independent, which is essential for long-term industrial adoption.

Overall, the technical validation confirms that substantial CO₂ reductions can be achieved while maintaining DS/EN compliance, durability performance and industrial stability.

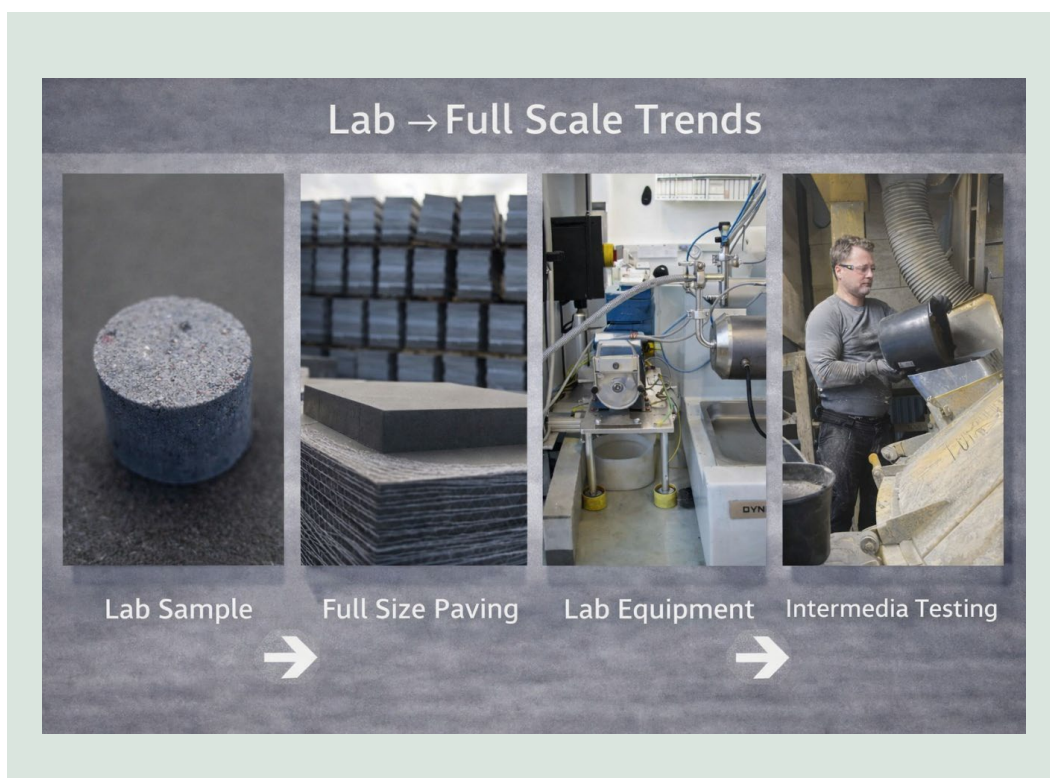


FIGURE 8. Transition from laboratory validation to full-scale production.
Illustration of scaling behaviour demonstrating preservation of performance trends during industrial implementation.

6. Industrial Implementation and Market Readiness

The decisive test of the WARM project was not whether the TriSi platform could perform in controlled laboratory conditions, but whether it could function reliably within a high-volume industrial dry-press production environment.

Laboratory optimisation had already demonstrated compliance with relevant mechanical requirements. However, compliance with DS/EN 1338 and DS/EN 1339 under industrial production conditions was regarded as the true benchmark of success. Industrial production introduces variables that cannot be fully replicated at laboratory scale: moisture variation in aggregates, fluctuations in ambient temperature, compaction dynamics, dosing tolerances and the operational realities of continuous production.

The central uncertainty prior to implementation was therefore not ultimate strength, but process tolerance and operational robustness.

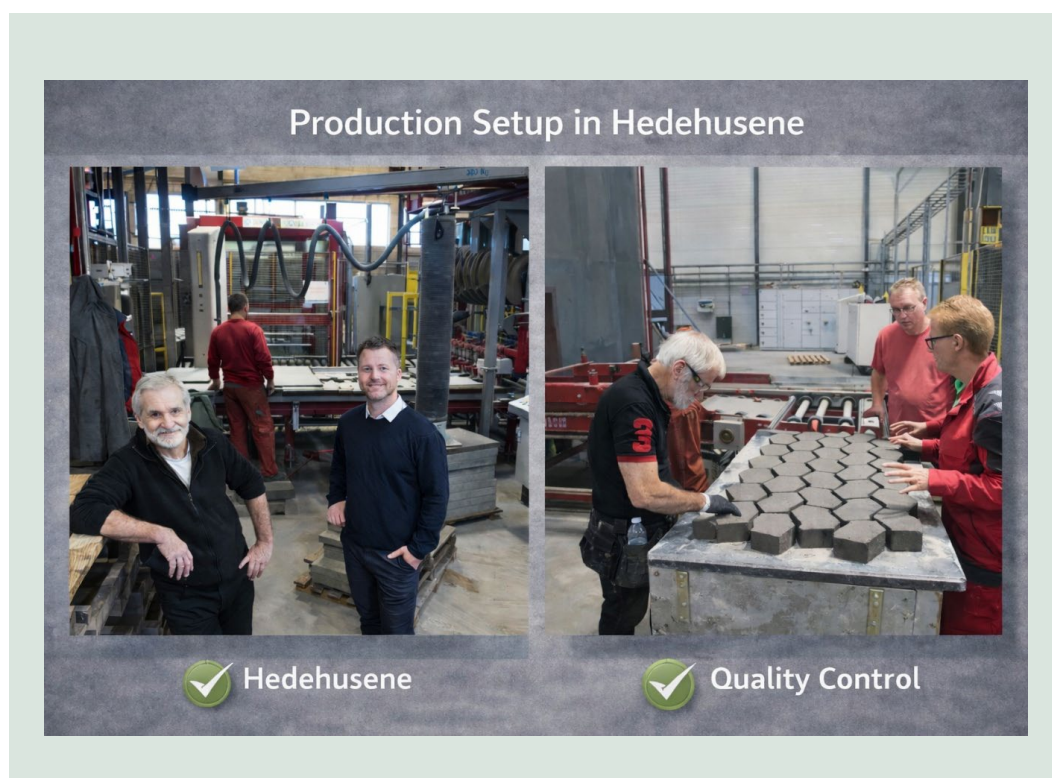


FIGURE 9. Lighthouse production setup in Hedehusene.

Full-scale dry-cast production line where the TriSi platform was implemented and validated under industrial operating conditions.

Implementation at the Hedehusene lighthouse facility was carried out in close coordination between CC and IBF. While CC provided the technological foundation and optimised mix designs, IBF undertook the physical integration of the binder system into existing production infrastructure. This included installation of additional silo capacity, adaptation of feeding systems and updating of control parameters in order to accommodate revised dosing sequences.

The initial production phase revealed predictable but important adjustments. The aluminosilicate-based binder exhibited a slightly different early-age reaction profile compared to conventional high-clinker OPC systems. Minor variations in water content or dosing precision had a critical influence during the early optimisation phase. These effects did not indicate structural instability, but rather required improved control of process parameters and operational familiarisation.

Through iterative adjustment of water dosage, mixing duration and compaction timing, stable production conditions were achieved. Once calibrated, the production line operated without reduction in throughput, increase in reject rates or compromise in dimensional stability.



FIGURE 10. Process modifications implemented for binder integration.
Additional silo capacity and adjusted dosing and control systems required for integration of aluminosilicate-based binder components.

Crucially, finished products consistently met the mechanical and dimensional requirements defined in DS/EN 1338 and DS/EN 1339. This compliance confirms that the TriSi platform is not merely environmentally advantageous, but technically equivalent to established paving products within regulatory frameworks.

A key observation was that long-term strength development was reproducible, even when variability in early age strength was slightly higher. This confirmed that the fundamental reaction mechanisms of the binder platform are robust under industrial conditions and that early sensitivity can be managed through procedural optimisation.

Organisational adaptation also played a role. Production personnel required familiarisation with the new material behaviour and revised quality control focus. However, once operational understanding was established, the binder system did not introduce additional procedural complexity compared to conventional production. The learning curve was measurable but limited in duration.

From a market perspective, the decisive question was whether the improved environmental performance would introduce structural cost penalties.

Material optimisation within WARM was therefore continuously balanced against economic feasibility. The hybrid binder composition was adjusted not only to maximise clinker substitution, but also to avoid unnecessary use of high-cost specialty materials.

The earliest attempts to substitute clinker with alternative binder materials reduced CO₂ emissions by 50% but also resulted in a product that was moderately more expensive in materials than IBF's equivalent standard product, manufactured using OPC. After many more iterations the final development step, undertaken at the close of 2025, resulted in a product with CO₂ emission reductions as high as 57% and material costs that match or are slightly less than IBF's equivalent standard product, even taking into account the license fee to use the Intellectual Property of the TriαSi platform.

This balance between CO₂ reduction and cost competitiveness is critical. A technically successful product that cannot compete economically will not scale. The WARM project demonstrates that substantial emission reductions can be integrated into existing pricing structures without requiring disruptive capital investment or the use of exotic raw materials.

The lighthouse implementation therefore demonstrates not only technical feasibility, but genuine market readiness. Contractors can install the products using standard procedures. Municipalities can integrate the products into climate accounting frameworks through verified EPDs. Production facilities can implement the technology through manageable modifications.

By validating the TriαSi platform under full-scale production, ensuring DS/EN compliance, maintaining economic competitiveness and demonstrating real-world installations, the project establishes a credible pathway for broader industry implementation.

7. Demonstration, Market Integration and Replication Potential

The WARM project was conceived not only as a technology development initiative, but as a full-scale demonstration of industrial applicability. The establishment of the lighthouse production facility in Hedehusene marked the transition from laboratory validation to full-scale industrial implementation.

The lighthouse project has served two purposes. Internally, it has enabled systematic validation of the TriαSi platform under industrial production conditions. Externally, it has provided tangible evidence that low-CO₂ paving products can be manufactured, delivered and installed within existing industrial frameworks.



FIGURE 11. Lighthouse production facility in Hedehusene.

Full-scale implementation site where the TriαSi platform was integrated and validated under industrial production conditions.

Unlike pilot-scale installations, the Hedehusene facility operates under normal, everyday commercial conditions. This distinction is important. Demonstration in an isolated or subsidised setup does not guarantee industrial feasibility. Demonstration within a commercial production operation does.

The products manufactured at the lighthouse facility were subsequently installed in real-world projects. For example, TriαSi platform products have been employed to create municipal pavements in Næstved, urban development areas such as Fælledby and charging infrastructure installations in Ejby, as well many other installations.

These installations confirm that the developed products can be specified, delivered and installed without modification of standard contractor procedures. From a practical perspective, this reduces the adoption barrier significantly. Contractors are not required to adjust laying techniques, and municipalities can incorporate the products within existing procurement structures.

The completion of verified EPD documentation further strengthens market integration. Environmental performance can be transparently documented and incorporated into climate accounting tools and tender requirements. This alignment between technical performance and regulatory documentation is essential for large-scale uptake.

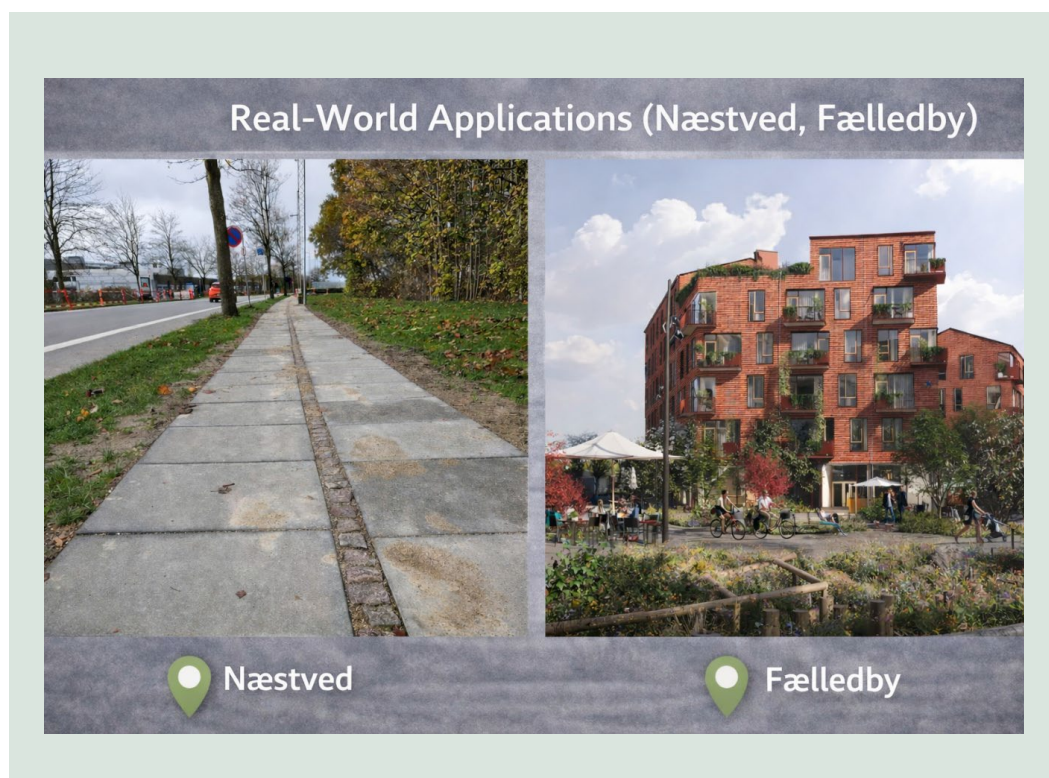


FIGURE 12. Real-world applications of WARM paving products.

Examples of installed TriαSi platform paving stones demonstrating functionality, durability and aesthetic integration in municipal and urban contexts.

The transition from a niche RELOW product to a broader standard product range represents an additional maturity step. The RELOW product demonstrates the upper boundary of CO₂ reduction achievable within the current platform. The standard range, optimised for broad deployment, confirms that environmental improvements can be reconciled with logistical and economic realities.

From an implementation perspective, the WARM project demonstrates that adoption does not depend on proprietary machinery or extraordinary capital expenditure. The modifications implemented at the lighthouse facility fall within conventional industrial adaptation practices. This lowers the threshold for implementation at additional sites.

The demonstration phase therefore confirms more than technical feasibility. It confirms market readiness. The TriαSi platform has been shown to function within regulatory frameworks, within commercial pricing structures and within practical construction workflows.

The significance of this demonstration lies in its scalability. Concrete paving stones represent a high-volume product category. When emission reductions of 40-57% are applied at scale, the cumulative climate impact becomes significant.

WARM thus functions not only as a successful project, but as a reference model for industrial transition within the paving sector.

8. Environmental Framework and Structural Impact

The environmental performance of the TriqSi platform products has been documented through Life Cycle Assessment (LCA) modelling in accordance with applicable product category rules and EPD requirements. From the outset, the environmental documentation was treated not as a supplementary exercise, but as an integrated part of the validation of the technological platform.

The primary analytical focus has been the A1-A3 system boundaries, covering raw material extraction, transport to the production site and manufacturing processes. This methodological choice reflects the structural emission profile of concrete paving products. For dry-pressed paving stones, the dominant contribution to global warming potential originates from clinker production and binder-related processes. By targeting these phases, the WARM project addresses the principal emission drivers rather than peripheral lifecycle stages.

The reference product for comparison is a conventional 7 cm paving stone with a documented 2021 baseline of 18.7 kg CO₂/m². Against this reference, the WARM project demonstrates reductions of approximately 57% for the RELOW product and approximately 40% for the standard product range within A1-A3 boundaries.

The environmental documentation is anchored in two completed Environmental Product Declarations developed using EPD Norge software. The RELOW EPD is based on site-specific production data from the Hedehusene lighthouse facility, ensuring direct alignment between industrial implementation and declared environmental performance. The standard product range is documented through averaged production data across IBF sites, allowing delivery under a consolidated EPD framework applicable beyond the lighthouse installation.

This dual structure strengthens both credibility and applicability: site-specific validation confirms technical feasibility under real production conditions, while multi-site averaging ensures market scalability.

Data collection was based on documented material consumption, metered energy usage, supplier-specific datasets and transport assumptions consistent with EPD rules. Where generic background data were applied, conservative assumptions were used to avoid overstating environmental benefits.

An independent LCA analyst (formerly DTU) reviewed the modelling framework, value chains and allocation principles. The review included cross-checking of input data, evaluation of emission factors and on-site verification of the RELOW production at the Hedehusene facility. This independent scrutiny ensures that the reported reductions are grounded in actual industrial practice rather than theoretical modelling scenarios.

A central question in evaluating environmental robustness is parameter sensitivity. In the case of WARM, the dominant driver of emission reduction is clinker substitution through the TriqSi platform. Variations in transport distances or electricity mix influence the absolute GWP values, but do not alter the structural reduction effect derived from reduced clinker demand.

As Denmark's electricity and energy supply continues to decarbonise, A3 emissions are expected to decline further. This dynamic effect is illustrated in FIGURE 13, which shows the trajectory from the 2021 baseline through verified 2025 values towards projected 2030 levels.

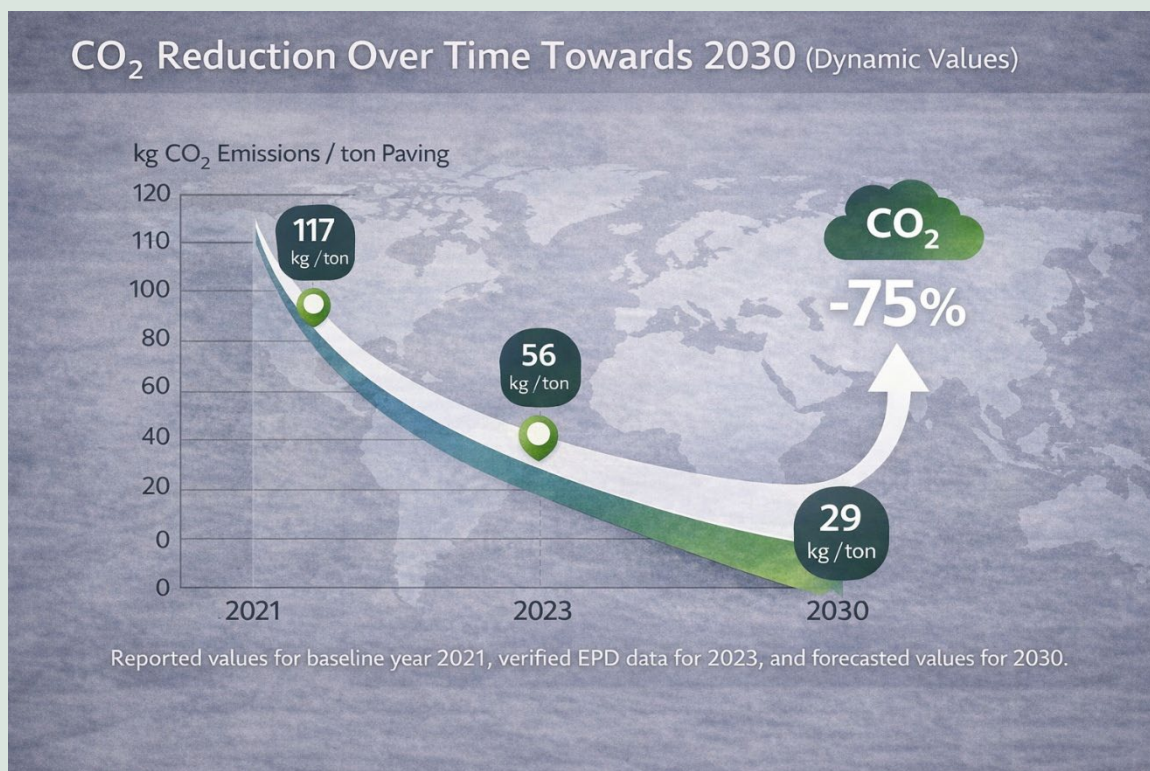


FIGURE 13. CO₂ reduction trajectory from 2021 baseline to projected 2030 levels.

Illustration of structural emission reductions achieved through binder optimisation combined with systemic energy decarbonisation.

The reductions demonstrated in WARM are therefore not dependent on offset mechanisms or accounting adjustments. They are intrinsic to the material composition and production process. This distinction is important in the context of long-term climate accounting and evolving regulatory frameworks, where structural decarbonisation is increasingly prioritised over compensatory measures.

Uncertainty in LCA modelling is unavoidable, particularly with respect to future energy mix assumptions and supplier variability. However, because the primary reduction mechanism is material substitution rather than marginal parameter adjustment, the magnitude of reduction is readily demonstrated and remains robust across reasonable sensitivity intervals.

Beyond CO₂ reduction, the WARM project contributes to broader environmental objectives through reduced clinker consumption, integration of waste-derived materials and elimination of superplasticizers in formulations. These aspects support circular economy principles and reduce reliance on environmentally problematic substances.

Taken together, the environmental framework underpinning WARM demonstrates not only quantifiable emission reductions, but structural decarbonisation within a high-volume product category. The combination of verified EPDs, independent review and full-scale industrial implementation provides a transparent and credible foundation for long-term adoption.

9. Dissemination of project results



FIGURE 14. Dissemination of project result.

WARM Project results have been disseminated through a multi-channel approach, combining full-scale demonstrations, public events, digital platforms, and targeted industry engagement. This strategy has ensured broad visibility while enabling direct dialogue with key stakeholders, supporting the adoption and implementation of low-CO₂ paving solutions.

- ECC has contacted a number of Danish local authorities and made them aware of the possibility of reducing their CO₂ emissions by employing the low CO₂ paving stones demonstrated in the WARM project. In general, it can be said that all the local authorities contacted showed an interest for low CO₂ paving.
- Digital platforms have served as a central pillar for communication efforts. Through the website, [Relow's website](#), ECC and STEKKER have established a knowledge hub where interested parties can access leading edge information about the project.
- In parallel with (b), **LinkedIn** has been used as a dissemination channel to reach professionals across the construction and materials sectors. The interactive nature of LinkedIn has also facilitated dialogue, feedback, and networking, strengthening the project's relevance and reach.
- Participation in major industry events have also been an important part of the dissemination efforts. At **BYGGERI'23** and **BYGGERI'25**, two of Denmark's largest construction exhibitions, ECC and STEKKER presented the WARM project to a broad audience including contractors, consultants, suppliers, and public stakeholders.
- The participation of ECC and STEKKER in **Building Green 2025** enabled the project partners to engage with a highly targeted audience focused on sustainable

construction. Here, the emphasis was on communicating how the WARM project contributes to reducing CO₂ emissions and enabling more resource-efficient building practices.

- (f) The project has also been presented at a range of thematic events aimed at both professionals and broader audiences. At the **MUDP information meeting in Odense (2023)**, ECC contributed to knowledge exchange within the MUDP community, sharing early insights and learning points from the project.
- (g) **Ressource City in Næstved (2023)**, the focus was on green solutions and the challenges faced by companies trying to develop new green solutions. This provided an opportunity to position WARM within a broader context of circular economy and resource optimization, highlighting how new binder technologies, such as the TriSi platform, can contribute to reduced environmental impact.
- (h) Participation in the **Climate People's Meeting (Klimafolkemødet) in 2024** allowed ECC to communicate the project's relevance to a wider public audience, including policymakers, NGOs, and citizens. This setting emphasized the societal importance of reducing emissions in the construction sector and demonstrated how technical innovation can support climate goals.
- (i) Beyond formal events, dissemination has also taken place through targeted collaboration and dialogue with key industry players. Engagements with organizations such as **Henning Larsen (2025)**, **Fælledby** and **1til1Landskab (2025)** have enabled in-depth discussions about integrating TriSi platform solutions into real projects. These interactions resulted in the use of the TriSi RELOW paving material for paving the Fælledby district of Copenhagen. In addition, the contractors informed the project partners that, if possible, they intended to employ TriSi RELOW paving material for any additional paved areas that would be laid as the Fælledby district expands.
- (j) Participation in **HÅNDVÆRK 2025** contributed to reaching practitioners and craftsmen, ensuring that knowledge is not only shared at a management level but also translated into practical understanding among those working directly with installing materials on site.
- (k) The project has also been disseminated through established professional networks and technical forums. Presentations at the **General Assembly of the Danish Concrete Society (2026)** have ensured that the project's findings are shared with experts and specialists in concrete technology.
- (l) In addition, the **IDA event "Learn more about calcined clay and alkali-activated concrete" (2026)** provided a platform for deeper technical communication. Here, the focus was on describing the performance characteristics, and potential applications of the technologies developed within the TriSi platform. Such forums are critical in fostering acceptance of new solutions in a traditionally conservative industry.
- (m) IBF's webpage also includes descriptions of the efforts that IBF have undertaken to reduce the CO₂ footprint of their activities.

9.1 Overall Impact of Dissemination Activities

Through this combination of digital communication, large-scale exhibitions, targeted events, and direct stakeholder engagement, the WARM project has achieved a high level of visibility and industry interaction. The dissemination efforts have not only communicated results but have also facilitated knowledge exchange, feedback, and collaboration.

This continuous dialogue with the industry has been instrumental in validating the project's direction, identifying barriers to implementation, and accelerating the pathway from development to real-world application. Ultimately, the dissemination strategy has supported the overarching goal of the WARM project: to enable the transition towards more sustainable construction practices through innovation, collaboration, and knowledge sharing.

Resume

The WARM project demonstrates that the next generation of low-carbon concrete is no longer a future ambition, it is already industrially achievable today.

At the core of the project lies the TriqSi™ platform, a flexible activated aluminosilicate technology platform enabling both mainstream concrete products and leading-edge low-carbon solutions. Through industrial implementation, optimisation and environmental verification, the project has demonstrated CO2 reductions of more than 50%, with RELOW products approaching 60% reduction compared to conventional reference products.

Building directly on the RELO research project, WARM has successfully translated the TriqSi™ platform from laboratory development into full-scale industrial production through this MUDP-supported lighthouse project. The project validates that activated aluminosilicate binder systems can replace a substantial share of conventional clinker while maintaining industrial robustness, DS/EN compliance, durability and economic competitiveness.

Beyond climate impact, WARM demonstrates how future concrete production can become significantly more resource-efficient and circular. The project documents large-scale integration of recycled concrete aggregates, reduced dependency on virgin raw materials and near zero-waste production strategies, where rejected concrete components can be directly reintroduced into production. In several cases, recycled concrete availability became the limiting factor rather than technical feasibility, highlighting a fundamental shift in how concrete waste may be viewed in future construction systems.

The results presented in this report demonstrate that the technological foundation required to meet, and potentially exceed, the original 2030 climate ambitions for the concrete industry already exists today.



Miljøstyrelsen
Lerchesgade 35
5000 Odense C

www.mst.dk