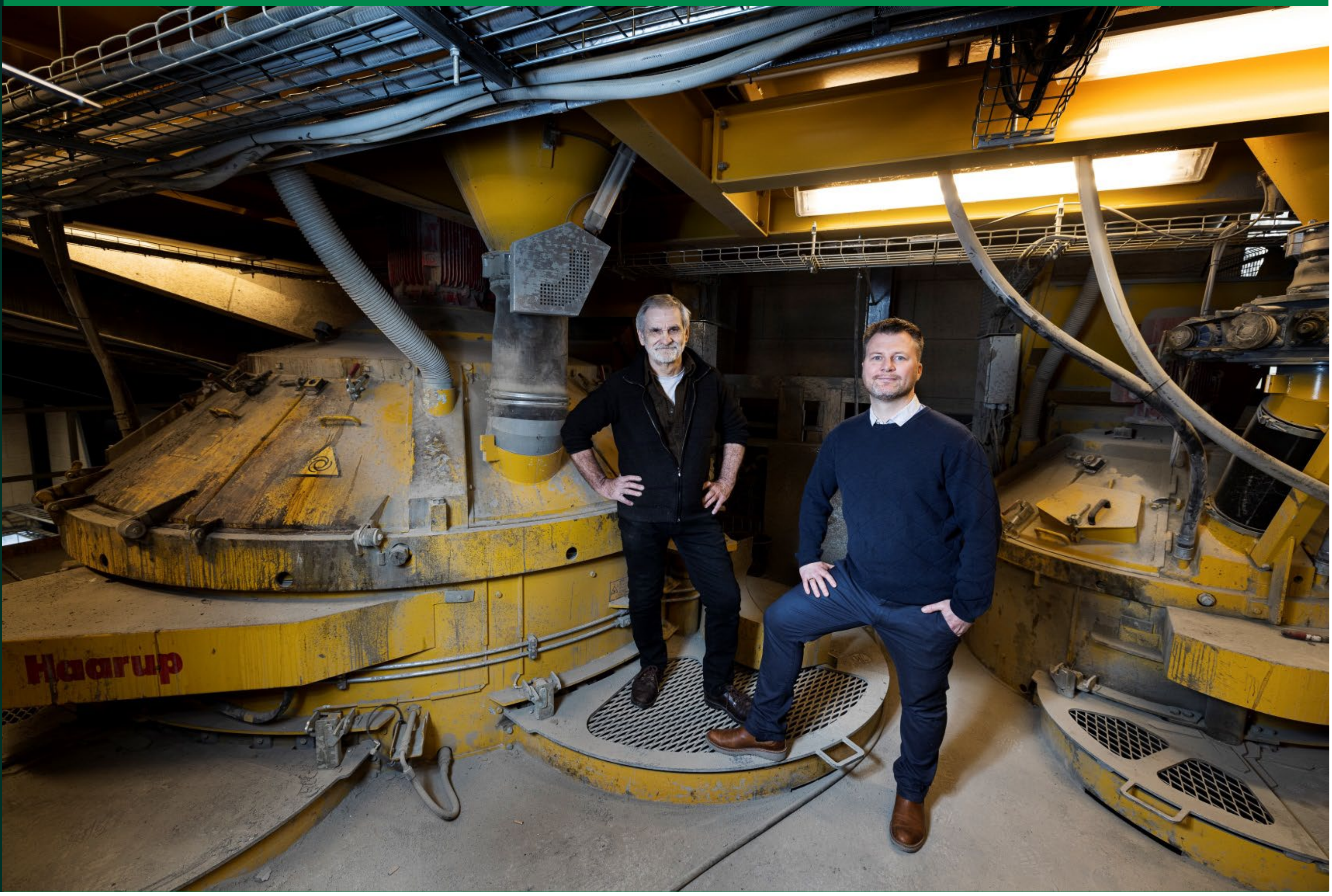
Ministry of Environment of Denmark
Environmental Protection Agency

RELO-Sten
Recyclable, low emission paving stones

MUDP report

September 2024



Publisher: The Danish Environmental Protection Agency

Editors:
Stuart Clyens
Christian Løjtved, ECC

Photos:
Joachim Rode: Forsidefoto
Stuart Clyens: Øvrige

ISBN: 978-87-7038-653-1

The Danish Environmental Protection Agency publishes reports and paper s 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.

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
Tolderlundsvej 5, 5000 Odense| Tlf. +45 72 54 40 00

Mail: ecoinnovation@mst.dk
Web: www.mudp.dk

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

Contents

SUMMARY

The RELO project has successfully developed and validated a binder material, manufactured using waste materials, which can be used to bond sand (including flint sands) and stone aggregates into a concrete whose CO_2 footprint is presently 53% lower than the CO_2 footprint of concrete manufactured using conventional Ordinary Portland Cement. It should be noted that the CO_2 footprint is expected to fall even further as green sources of energy become more widely available.

The RELO binder has been tested, under industrial conditions, by manually feeding RELO material into industrial equipment which was then used to produce a “proof of principle” batches of low CO_2 foot print, paving stones. Following the production tests, the paving stones were themselves tested and found to meet the DS/EN standards that paving stones must meet before being released for general use.

This report discusses the CO_2 emissions related to the European building industry with a focus on emissions related to cement and concrete production. The development of the RELO binder and the methods used to test concretes made from the binder are outlined. Potential future uses of the RELO binder for the production of a range of products are also discussed. Finally, the steps that have been taken to disseminate the information concerning the RELO binder and its potential uses are described.

1. BACKGROUND

1.1 World Perspective

CO_2 Emissions

Presently the cement industry is responsible for approximately 8% of the world's anthropogenic CO_2 emissions – a greater share than any country other than China or the US [1].

Global cement production has increased more than 30-fold since 1950, almost 4-fold since 1990, and is predicted to rise further as global urbanisation and economic development increases the demand for new buildings and infrastructure (Andrew, 2018). Although the average CO_2 emissions per tonne of cement produced has fallen by 18% globally over the past few decades, the building sectors' overall CO_2 emissions have risen significantly, with demand tripling since 1990 [2].

In addition, the built environment requires the use of very large amounts of material and, in some cases, this has resulted in certain material sources coming under pressure. One example is the inappropriate removal of sand from river banks which has resulted in major damage to the environment that will take decades if not centuries to repair [3].

In order to meet the Paris Agreement's global temperature goals the cement industry will need to dramatically cut its emissions [4]. The International Energy Agency (IEA) and the industry-led Cement Sustainability Initiative (CSI) recently released a new low carbon roadmap [5], indicating how emissions might be reduced to meet a "2°C global temperature rise scenario" and a "below 2°C" scenario. The IEA roadmap assumes cement demand will increase 12-23% by 2050 and for a 2°C scenario to have a 50% chance of limiting the global temperature rise to 2°C above pre-industrial levels by 2100, the roadmap indicates that cement emissions must be reduced by 24%. It is worth noting that the Paris Agreement [6], actually calls for a global temperature rise to stay below 2°C.

At the recent "Made in More Sustainable Concrete" conference held in Copenhagen 2022, Professor John Provis [7] of Sheffield University, UK made an attempt to describe the magnitude of the problem facing the building industry regarding the contribution to global warming resulting from cement production. Professor Provis pointed out that, to meet the Paris Agreement's global temperature goals, the CO_2 emitted by all cement plants world-wide need to be captured and sequestered and that this would require the construction of one CO_2 capture unit every week from (2022) until 2050. In addition, to minimize the CO_2 emissions related to the capture units, the units would have to be both built and powered using green energy sources.

Waste materials

In addition to the problem of reducing anthropogenic CO_2 emissions, humankind also needs to address the problem of how to safely and economically dispose of the waste materials generated by human activity. Over the past 50 years there has been a steadily increasing focus on developing techniques and processes that use/treat waste materials so that they can be recycled and used in the production of other products thus creating a more sustainable, circular economy.

In the case of concrete, research has shown that certain waste materials (e.g. fly ash, bottom ash from municipal incineration plants) exhibit varying degrees of pozzolonic activity and can be used to partially replace the OPC used in concrete production.

8%

The cement and concrete industry is responsible for about 8% of global carbon dioxide emissions!

Green Energy Sources
The stepping stone towards zero emission for the RELO binder.

However, before any waste material can be considered for use in concrete production, the quantities and long-term availability of the waste material must be thoroughly assessed. In the RELO project, attention has been paid to identifying/testing only waste materials that are cheap and widely available in large quantities. One of the materials identified for use in the RELO project is presently being partially disposed of in landfill sites. If the fraction being disposed of in landfill sites can be used in the production of the RELO binder it will provide the last step in establishing a circular economy for this material in Denmark.

1.2 European Dimension

Presently the building industry is responsible for 30% of the industrial employment within the European Union (EU) and contributes approximately 10% to the gross domestic product of the EU [8]. However, the construction industry is also known to be the highest energy consumer in the EU, accounting for 40% of the total energy consumption and contributing almost 36% of the EU's total greenhouse gas (GHG) emissions [9].

40%

Of the total energy in EU is consumed by the construction industry

1.3 CO_2 Emissions

The Technology Roadmap - Low-Carbon Transition in the Cement Industry published by the International Energy Agency [5] has identified a number of areas of action whose implementation could lead to a significant reduction of CO_2 emissions from the cement industry. These action areas are as follows:

A. The introduction of more efficient cement kilns to make cement production less energy-intensive. Global average energy use per tonne of cement is approximately 20% higher than production with current best available technology and practice [2].

B. The use of alternative fuels – for example, the use biomass or waste in place of coal has reduced emissions. This is especially the case in Europe, where around 43% of fuel consumption now comes from alternatives [10].

C. Reducing emissions using carbon capture and storage (CCS) technology [11]. This technology has not yet been widely employed by the cement industry (except trials at Norcem Brevik [12]), but the IEA roadmap assumes integration of CCS in the cement sector will reach commercial-scale deployment by 2030. Uncertainty [13] over the potential to rapidly scale-up CCS and its large cost [14] are major barriers to its use in reducing concrete emissions.

D. Reducing emissions by lowering the proportion of Portland clinker in cement [5]. Low clinker ratio cements have the potential to reduce emissions per kilogram by up to four times. The IEA roadmap sets a target average global clinker ratio of 0.60 by 2050 (down from 0.65) However, this is a significant challenge as it would require around 40% more clinker substitutes by 2050 than today, whilst it is expected that the availability of traditional substitutes – fly ash and blast-furnace slag – will likely begin to fall.

E. The development of novel cements, which do away with the need for Portland clinker, altogether e.g. cements based on calcined clay [15]. To date these cements have proved expensive to manufacture. However, there is now a great deal of research being carried out in this area and if such types of cements could rival the cost and performance of Portland cement, they would offer a way to significantly reduce emissions. To date, none have yet achieved large-scale commercial use and are currently used only in niche applications e.g. coating sewer pipes to increase acid resistance [15]

Recycled Concrete
Strengthening the circular economy to reduce the pressure on landfill sites.

F. The use of waste and recycled materials (e.g. crushed concrete) which can be added to a fresh concrete mixture to e.g. add strength or act as a filler to reduce porosity.

1.4 Project Aims

The RELO project has mainly focussed its efforts on action area (e) and (f) described above. The aim of the RELO project has been to develop and validate an alternative binder to Ordinary Portland Cement (OPC) which can be used to manufacture a concrete that can meet the following specifications:

I. A concrete that has a CO_2 emission footprint 45-50% lower than an equivalent, conventional, OPC based concrete.

II. A concrete that can be manufactured using a wide range of sand and stone aggregates including widely available flint sands which, if employed to manufacture concretes using conventional OPC, results in a concrete that is not suitable for applications involving long term exposure to water.

III. A concrete that can employ waste and recycled materials as strengthening additives, thereby establishing a circular economy for materials that would otherwise be disposed of in landfill sites.

Aim

45-50%

CO_2 reduction

It should be emphasised that strenuous efforts have been made to ensure that all raw/waste/recycled materials used for the RELO concrete can be sourced locally. In the case of materials that must be processed before being used, care has been taken to only employ materials that can/could be processed in Denmark using green energy. In other words, in the future, it should be possible to manufacture a RELO based concrete using materials entirely sourced and/or produced/processed within the borders of Denmark.

2. BINDER DEVELOPMENT

2.1 Mixture Design

All the initial research and development work described in this report was done at a laboratory scale. The mixers used for these tests were a Kenwood benchtop kitchen mixer, used to manufacture test batches of up to 2 kilograms, and a BAMA planetary mixer capable of mixing batches of materials up to 30 kilograms, see FIGURE 1.

FIGURE 1. Kenwood benchtop kitchen mixing unit capable of mixing 2-3 kg concrete batches (left) and BAMA planetary mixer capable of mixing 30 kg concrete batches (Right).

In order to ensure that results of laboratory scale mixing tests could also be reproduced using larger batch sizes, industrial scale, zero series, trials, involving batch sizes of tons, were also carried out in co-operation with the Danish paving stone manufacturer IBF who own and run 12 manufacturing facilities in Denmark. These industrial trials also involved qualifying the RELO paving stones by subjecting them to the test procedure laid down in the EU standards related to paving stones.

The first industrial trials were carried out at IBFs factory in Holmegaard, at which the Coloc blocks in FIGURE 3 were manufactured. Subsequent tests were carried out in the Hedehusene, on a newer production unit, which allows the adjustment of several parameters. Test was also carried out at IBFs laboratory.

The Hedehusene factory comprises a fully automatic, computer controlled, mixing unit, capable of mixing batches of up to 2.5 tons, see FIGURE 2. The raw materials required for a mixture were fed into the mixing-unit from a series of silos connected to the mixer via conveyor belts. After mixing the mixed material was allow to exit the base of the mixer and fed into the forms of a gyro-compactor which vibrates and compresses the mixed material into semi-finished products with a sufficient green strength to maintain shape.

FIGURE 2. IBF's Industrial mixing unit capable of mixing 2.5 ton concrete batches.

The geometry of the semi-finished products depends on the form used. FIGURE 3 (left) shows a batch of so-called Coloc blocks, produced from RELO material, just after ejection from the gyro-compactor in Holmegaard. It can be seen that the Coloc blocks are resting on a baseplate. In order to convert the semi-finished, lower green strength, stones into finished, high strength stones, the stones are initially stored at room temperature in a controlled humid atmosphere.

FIGURE 3. Green state, Coloc blocks (left) and Paving stones (right), directly after ejection from IBF's vibration compression unit.

Curing was the final phase of the production process and involves automatically transporting the stones, still positioned on the baseplate, into the curing area. The base plates carrying the green-state paving material are then stacked into racks and moved into a storage room for a period of approximately 24 hours. The paving stones are then moved from the storage room, removed from the racks, stacked on pallets and ready for delivery to an end user.

2.2 Particle Distribution

Particle size analysis is a process in which a sample of material is examined to identify its particle size distribution and is usually presented as a distribution curve, which illustrates the amount of material that passes through a given sieve size.

Based on the particle distribution curves and densities, it is possible to determine the optimal ratio of materials that provides the best packing of the individual particles. The maximum strength that any given binder can achieve usually corresponds to a mixture containing a minimum amount of pores, however in practice a certain percent is desirable as this improves the freeze thaw properties. Whereas to big air pockets can give rise to increased water absorption, which is not desirable as it can result in cracks.

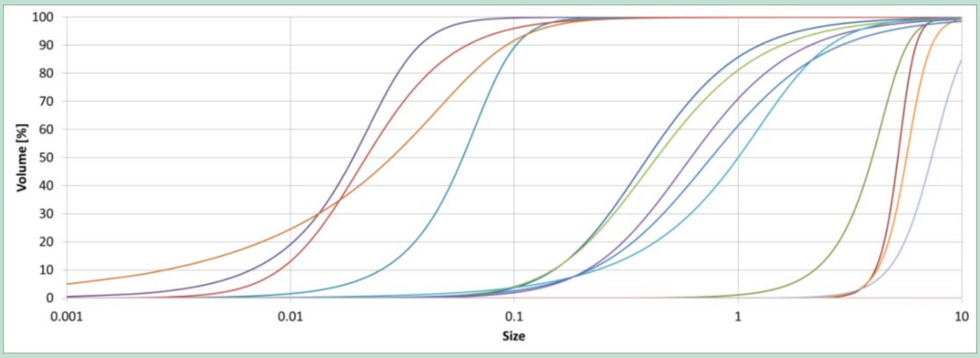


FIGURE 4. Particle distribution curves determined during the RELO project.

The Particle Size Distribution (PSD) inputs have been used as input for packing models, a model which can be divided into types, a discrete model and a continuous model. The discrete model assumes one uniform sized aggregate. In contrast the continuous model employs a model in which the aggregate is assumed to comprise a range of particle sizes, which more realistically reflects the results of the PSD curves.

The “Elkem Materials Mixture Analyser” software has been used to analyse and optimise the packing in the RELO project. The software is based on the modified Andreassen model [17] but is limited to spherical particles, which is not completely satisfactory. However, the software is simple to use and based on a continuous packing model. In the opinion of the authors of this report it is preferable to the more expensive and very complicated models developed by De Larrard [18] which combine particle packing, angularity and rheology.

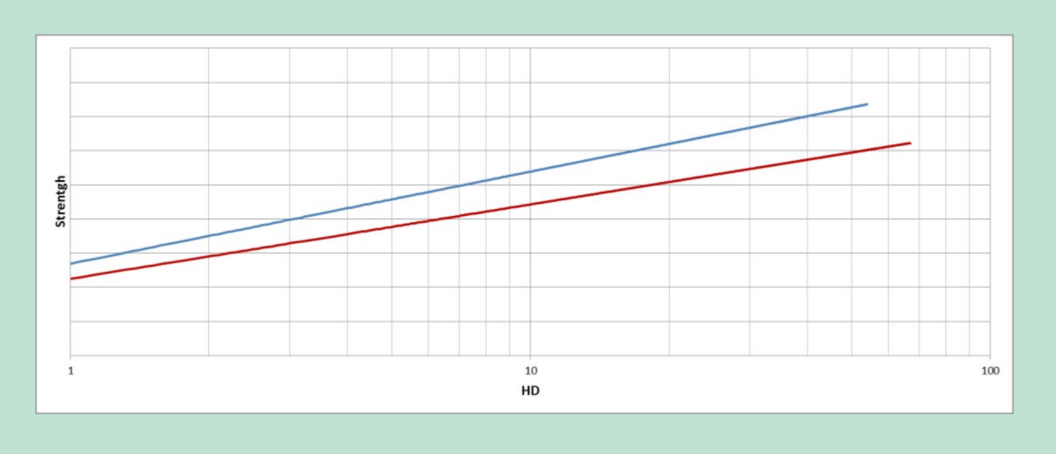
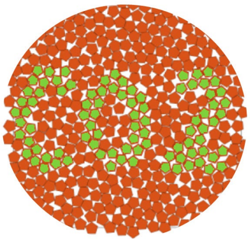


FIGURE 5. Typical compressive strength versus curing time (Hardening Days) curve for a RELO material based concrete for two different mixtures of aggregate employing an identical binder.

An intensive study has been carried out to identify the relationship between the packing achieved for different concrete mixture designs and the performance of the concrete, mainly in terms of mechanical strength. The initial results of this work are shown in Figure x, where the blue curve shows the strength development of an improved mixture design, achieved through modelling, together with the red curve which shows the strength versus curing time for an earlier mixture design with a less dense packing.

The software has proved to be a very useful screening tool in that it can be used to identify potential compositions and cut down the number of trials.



Packing
Particle packing techniques for sustainable concrete

TABLE 1. Benefits of the particle packing modelling techniques.

Benefits:
Reduction in the cement/binder ratio
Design of special concretes
Reduction in the number of trials
Lower porosity/permeability to achieve lower water absorption

2.3 Crushed Concrete

Another objective of the RELO project was to limit the use of scarce resources. A goal that has been achieved through, not only the use of waste materials from other industries not related to concrete, but also through the recycling of concrete, in the form of crushed concrete. Laboratory experiments have shown how the RELO material can be crushed and reused as aggregate in the production of new RELO products. This is a crucial part of IBF's Zero Waste Philosophy, which involves recycling 100% of the residual waste resulting from scraped products with visual and other defects. These defect products are crushed and recycled in the form of aggregate. The proportion used is sufficient to achieve zero waste and is within norms and standards related to manufacturing fresh concrete using recycled concrete as an aggregate.

2.4 Waste and Recycled Materials

One of the main objectives with the RELO project has been to use waste materials, to minimize/eliminate the need for landfill deposition. However, the use of waste materials can also have several other advantages. Firstly, the use of recycled material or waste materials in concrete can reduce the amount of virgin raw material that must be sourced and extracted from nature. Secondly, if the particle size of a waste material is small enough to pack between bigger particles used in a concrete mix, then its use can lead to an improvement in mechanical properties and reduce water absorption.

In addition, some waste materials are the result of processes which can impact/increase cementitious properties with the result that, when used as a concrete-additive, these materials improve mechanical properties, e.g. slag which is a by-product of steel making and is produced when silicates and metal oxides, present in the steel, solidify upon cooling.

It is the government's objective to promote a circular economy, including better (re)use of resources and prevention of waste
[21]

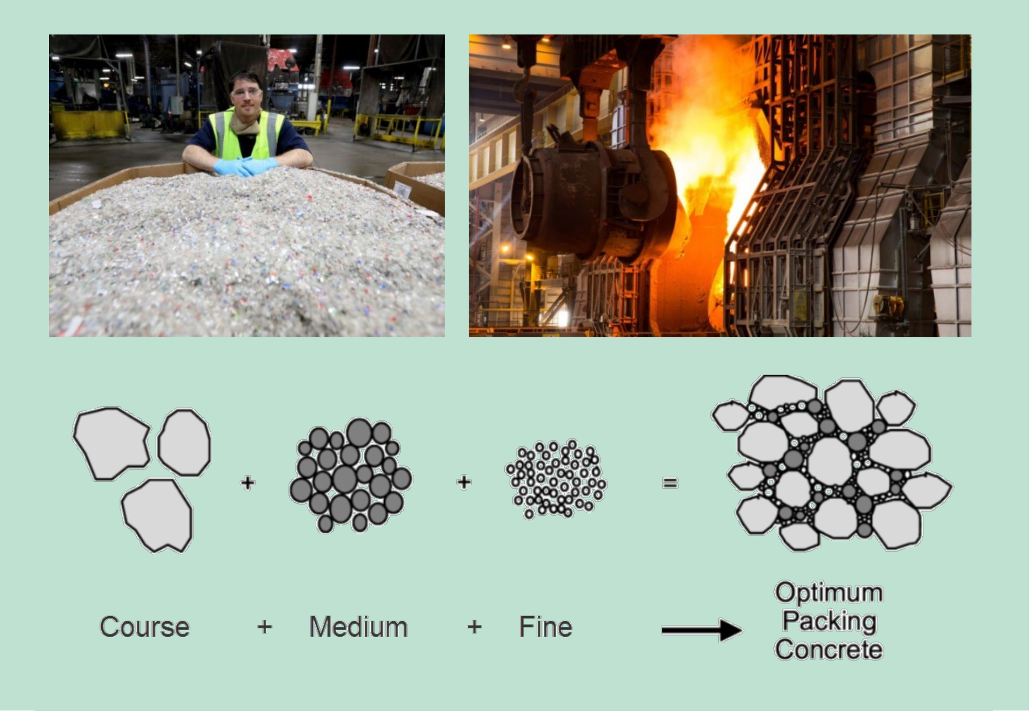


FIGURE 6. Potential benefits of using waste or recycled materials.

However, not all waste materials can be recycled, at least not directly, because some waste materials must be cleaned so that they are free from e.g. heavy metals, dioxins etc., which could result in irreparable damage to the environment if not removed. Therefore, it has been a prerequisite in the RELO project that, before being considered for use in the RELO project, any waste material must be, or could be, categorized as "Aggregate for concrete" according to EN 12620:2002 +A1:2008. This standard specifies the amounts and types of chemicals that are permissible in materials used as aggregates in concrete.

2.5 X-ray fluorescence

The silicate based re-cycled waste materials, selected by the RELO team, were subjected to XRF (X-ray fluorescence) analysis, which is a non-destructive analytical technique used to determine the elemental composition of materials.

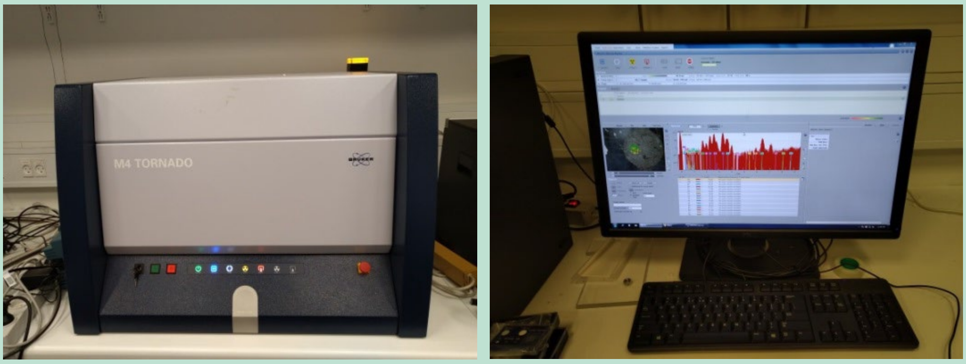


FIGURE 7. XRF machine, at DTU-RISØ, used to examine the waste materials in the RELO project.

The composition of the waste materials used in the RELO based concrete is critical. Ideally such waste material should not only act as fillers but should react and bond with the other materials comprising the concrete mix.

Depending on the waste material composition, it is possible to use the XRF results to adapt a binder composition so that the waste material participates in the chemical hardening process. The XRF result can also be used to show that the amount of heavy metals, do not exceed the allowable threshold as well as the amount of critical oxides present e.g. silicon dioxide (SiO_2), aluminium oxide (Al_2O_3) and iron oxide (Fe_2O_3).

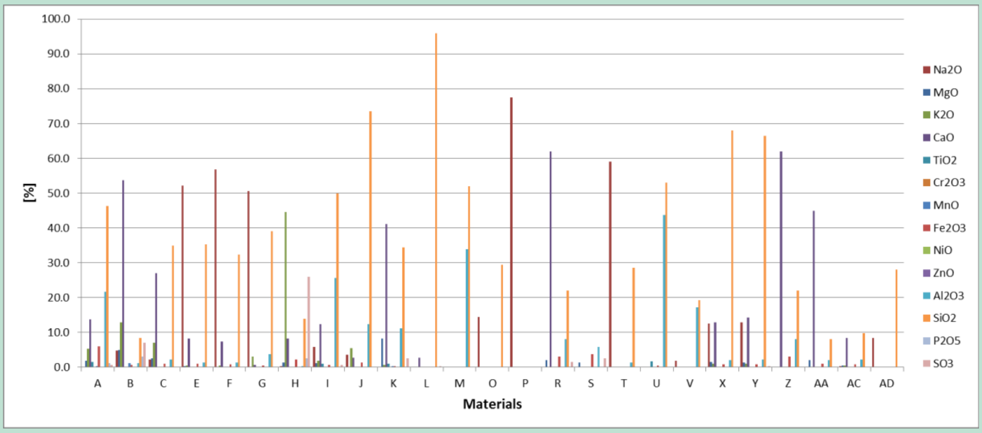


FIGURE 8. XRF results from 25 different additives tested during the RELO project, for which some are waste materials.

2.6 Activity Index

Waste materials that exhibited attractive compositions were examined in more detail to determine the amount of reactive material they contained. The reactivity of each material was characterised by its "pozzolanic reactivity" index.

The "pozzolanic reactivity" of a material can be determined using a standard test method outlined in the EU standard DS/EN 196-1. This test method is employed when e.g. fly ashes are tested as a replacement for cement was has therefore also been used in the RELO project to measure the "pozzolanic reactivity" of waste material considered for use in the manufacture of RELO concrete.

According to DS/EN 196-1 "Determination of the activity index", the method employed to determine the activity index of material requires replacing 25% of OPC from a standard mortar composition and replacing it with the material whose activity index is to be determined.
The compressive strength of standard prisms, manufactured from the mortar containing the material of interest, are then determined after 28 days curing and compared to the compressive strength of a mortar manufactured using only OPC and sand.

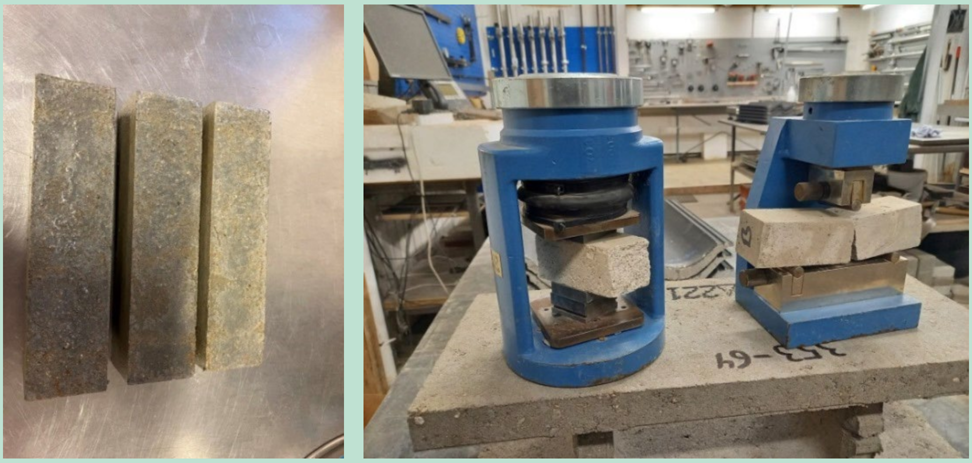


FIGURE 9. Intact mortar prisms made with 25% waste material replacement (left) and right prisms after test.

In the case of the RELO material. The results of the compressive strength tests, after 28 days curing, showed that waste material A, B and E did not immediately meet the requirements for "pozzolanic reactivity", as the compressive strength of mortar samples with added waste material added lower than the values required to meet EN 450-1, and would therefore have a negative effect on the concrete. Mechanical and chemical experiments were completed with the aim of improving the reactivity of these waste materials but the experiments showed that the CO_2 cost was too high.

TABLE 2. The activity index values for a 25% cement replacement.

	Req. cf. EN 450-1	A	B	C	D	E
28 HD	≥75%	71%	69%	85%	96%	61%
90 HD	≥85%	N/A	79%	89%	117%	62%

Waste material C and D, on the other hand, had a positive effect on the mortar samples as both of them exceeded the minimum "activity”, as outlined in EN 450-1.

The results for waste materials C and D indicated that they would probably improve strength if used hybrid RELO mixtures in which unreactive materials, such as sand, were partly replaced by these waste materials. Subsequent tests proved this to be the case and up to a 20% increase in compressive strength was achieved when these materials were used in the hybrid mixtures.

3. MECHANICAL TESTING

3.1 Compressive strength

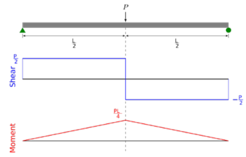
There are no EU standards related to the compressive strength that paving stones must possess. However, compressive strength tests are relatively simple to carry out and the compressive strengths of a wide range of conventional concretes are well documented. Therefore, for comparison purposes, a series of tests were carried out on cured RELO materials to determine compressive strength. The equipment used to measure the compressive strength is shown in FIGURE 10.

FIGURE 10. Hydraulic compressive strength tester.

The tests revealed that, depending on the mixture design, the compressive strength of RELO paving material was comparable to that of conventional paving stone material manufactured from Ordinary Portland Cement.
The results from the test further revealed a correlation between compressive strength, splitting strength and bending strength, which makes it possible to predict, for example, the bending strength of larger paving stones, based on the result of the compressive strength of smaller samples.

3.2 Splitting and Bending Strength

Although there are no EU standards related to the compressive strength of paving- blocks and stones, they must meet respectively DS/EN 1338 with regards to their splitting strength or DS/EN 1339 with regards to their bending strength. Therefore, the splitting strength or bending strength of paving components manufactured from RELO materials were measured according to the standards at IBF's material test facility in Hedehusene. The hydraulic test equipment and test set-up employed, for a bending strength test, is shown in FIGURE 11. As can be seen the bending strength test method used is effectively a three point bending test without torsion.



3-Point Bending
Illustration of shear and moment distribution of a three point bending test

In order to meet the standard used for paving material, after curing, a paving block must possess a minimum characteristic tensile splitting strength of 3.6 MPa (DS/EN 1338) or a characteristic bending strength not less than 4 MPa for a Class 2 paving stone (DS/EN 1339). Bending strength tests, carried out on a total of 70 RELO paving stones showed that they had a characteristic bending strength of 4.8 MPa and met the Class 2 strength requirement.

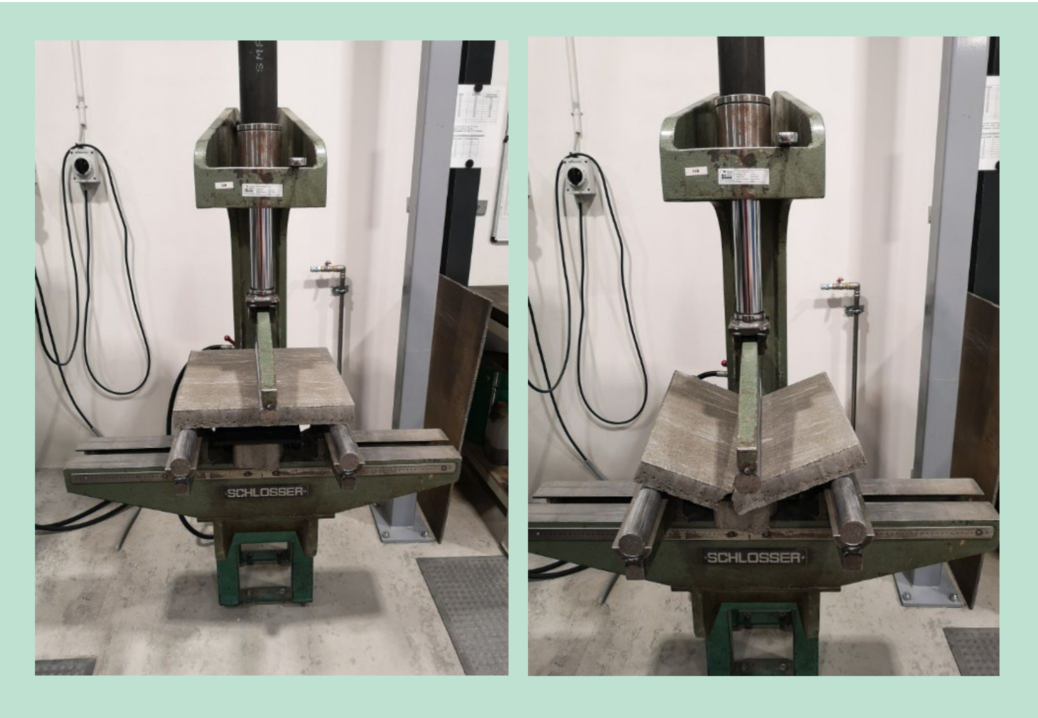


FIGURE 11. Hydraulic mechanical test equipment used to measure bending strength.

4.8MPa

Strength according to EN 1339:2003

3.3 Water Absorption

Water absorption tests were carried according to the procedures laid down in DS/EN standard 1339. This testing, which was also carried out at IBF's Hedehusene test centre, involves immersing test samples in water at a temperature of 20°C until they reach a constant mass (M_1). The specimen is then wiped with a cloth and placed in an oven at 105°C until it reaches constant mass (M_2). The water absorption Wa of each specimen as percentage of its mass is derived from the following equation:

$$Wa = (M_1 - M_2)/M_2 \cdot 100\%$$

According to the EN standard, the minimum period for both the wet and dry condition must be at least three days and a constant mass is deemed to have been reached when two weighing's performed at an interval of 24 hours show a difference in the mass of the specimen of less than 0.1%. The specimens shall be cooled to room temperature before weighing.

Non-Porous
It's practically impossible to make an absolutely nonporous concrete, as the concrete is inherently porous, but through packing technique and correct utilisation of the binder will improve the concrete surface to minimise water penetration.

The water absorption test was used as a screening test, because of its simplicity and cost. The more severe freeze thaw testing was conducted on RELO showing both promising strength and water absorption properties.

3.4 Freeze Thaw

Freeze thaw testing of RELO material was carried out according to the procedures laid down in DS/EN standard 1339. This testing, which was carried out at IBF's Hedehusene test centre, involves subjecting test specimens to 28 freeze thaw cycles (±20°C) while the surface is covered with 3% NaCl solution (de-icing salt).
The material that scaled off at the end of the 28 freeze cycles was collected and weighed and the results expressed in kilograms per square metre.

FIGURE 12. Left, specimens in freezer and right an example of a specimen with rubber sheet and salted water covering sides and top respectively.

0.2kg/m²

Loss of mass according to EN 1339:2003

According to the EN standard EN 1339:2003 the amount of material scaling from the surface of 3 paving stones, subjected to 28 freeze-thaw cycles should, on average, not exceed 1.0kg/m² and no single value should exceed 1.5kg/m². The freeze-thaw tests carried out on the RELO material showed that the amount of RELO material that the average amount of material that scaled off from 3 test paving stones was 0.2kg/m² with a maximum value for a single paving stone of 0.5kg/m².

4. ENVIRONMENTAL ASPECTS

4.1 CO_2 Emissions

As stated earlier in this report, the main aim of the RELO project was to develop material combinations and processes which would allow the manufacture of paving stones with a CO_2 footprint that is significantly lower (45-50%) than the CO_2 footprint of similar paving stones produced using conventional Ordinary Portland Cement (OPC).

In order to calculate the CO_2 footprint of paving stones manufactured using the RELO material it was necessary to first obtain reliable data regarding the CO_2 footprint of the individual materials used in the RELO mix.

To those not involved in determining the CO_2 footprint of products this might seem a reasonably simple and straightforward process involving looking up individual material CO_2 footprint values available, on-line, on material databases and then summing the values for each material.

In the case of some materials finding reliable CO_2 footprint values could be found relatively quickly, e.g. sand, stone and OPC which act as basis for comparison. However, for other materials accurately determining their CO_2 footprint was far from straightforward and required, not only time-consuming searches through the literature, but even more time-consuming work involving establishing a dialogue with suppliers to ensure up-to-date CO_2 footprint values (i.e. 2022 values) were being employed in the RELO project.

Through contacting suppliers, it soon became apparent that many regard the CO_2 footprint values of their materials as commercially sensitive and do not readily reveal values. It soon became clear that, in the case of geopolymer development work, this has led authors of very many scientific articles to quote obsolete energy/CO_2 values from work dating back to the 1990s. Another complication arises when a material can be manufactured using different processes, each producing the same material but with a different CO_2 footprint. In such a case it is essential to know and describe exactly which process a particular manufacturer has employed before an accurate CO_2 footprint value can be determined.

In addition, the source of the energy employed to produce a particular material is also critical in determining an accurate CO_2 footprint for the material. For example, the CO_2 footprint related to energy generated through the combustion of diesel and gas is significantly higher than that related to energy generated by solar and wind.

Due to the difficulties described above, those involved in the RELO project have built up specialised, in-house, LCI software with an associated database entirely focussed on the materials used in manufacturing RELO paving stones. Part of this work was carried in co-operation with environmental and concrete specialists employed by the Danish Technological University. The aims of constructing this, fully referenced, database were as follows (a) to accurately list CO_2 footprint values for all the materials involved in the RELO work together with a description of exactly how each CO_2 footprint was determined (b) to allow the impact on overall CO_2 foot print values to be quickly assessed for different material combinations.

An additional, independent check of the CO_2 footprint values for the RELO material was provided by IBFs own quality control department who carried out their own calculations using a Third Party Approved, EPD software drawing on data from the IBF's own material database.

The database has been developed in such a way that it allows the user to design concrete recipes, whilst CO_2, SEC and prices can be continuously updated and percentage-wise be compared to the values for conventional concrete and last but not least, the database forms a link between the different work packages of the RELO project allowing, information from each work package to be pooled.

The CO_2 footprint of the RELO material mixture, in terms of kg CO_2 emitted per kilogram of material, is shown in TABLE 3 together with the values for an equivalent concrete based on conventional Ordinary Portland Cement.

53%

Reduction in CO_2 emissions

TABLE 3. kg CO_2 emitted/kg of material.

Conventional concrete	RELO material based concrete	% reduction in CO_2 emissions
0.107	0.05	53%

The CO_2 values listed above are so called "A1" values as described in a recent document published by EPD Denmark [16]. "A1" values are values associated with the quarrying and production of the raw materials used in a production process. "A2" values are those associated with transporting raw materials to the locality where they will be processed. "A3" values are the values associated with carrying out the manufacturing process.

It should be noted that the sand and stone aggregate used in the RELO material, are drawn from the same sources of sand and stone aggregate already used by IBF in their conventional paving stone production. This has meant that, in terms of A2, values there is no significant difference in A2 values for the RELO and conventional OPC paving stone production.

The RELO project has almost entirely focussed on work which reduces A1 values as it is the processes associated with this value that dominates CO_2 emissions. As can be seen from FIGURE 14, 80% of the CO_2 emissions are associated with the processing of materials used for concrete production, of which cement is responsible for around 70%. In other words, the contribution of A2 and A3 activities to CO_2 emissions are relatively minor although, in IBFs case, the company are constantly trying to reduce the A3 value associated with production by regularly optimising their production equipment, including the increasing use of green energy produced from IBFs own solar cells units.

4.2 Potential Aspects Through New End-Uses

Support walls, kerb stones, stairways and grass support stones

IBF presently uses dry pressing methods to manufacture a range of interlocking concrete blocks that are employed in the construction of support walls (FIGURE 13 - a) as well as kerb stones (FIGURE 13 - b) massive blocks used in the construction of outdoor staircases (see FIGURE 13 - c) and hollow stone used for to provide support in grassed areas (see FIGURE 13 - d). As the RELO project has already demonstrated that RELO material can be formed into different geometries using dry pressing, all of the products listed above could potentially be manufactured from RELO material with a reduction in CO_2 emissions of 45-50%.

2050 NET ZERO

a) Interlocking blocks for support walls

b) Concrete kerb stones

c) Concrete stairway

d) Grass reinforcement stones

FIGURE 13. A range of cement-based products manufactured by the Danish company IBF [19].

All of the concrete products shown above may be regarded as being on the “low tech” end of the spectrum of concrete products. All of these products have one thing in common i.e. if they fail in service they can easily be replaced and there are no serious safety issues associated with failure.
It is envisaged that, once RELO paving stone production is established, scaling law established and the stones have met DS/EN standards and passed field testing, further experience with RELO material will be built up through the production of several, if not all, of the products shown above.
Having built up experience through the production of low tech RELO concrete products the manufacture of more technically demanding products, such as wet cast products discussed in the following section, could be considered.

Wet cast concrete
As stated above, the RELO project has focused on the development of mixtures for “low-tech” dry pressed concrete products for which the market is limited. In contrast, the market for wet cast concrete is much larger however, wet cast concrete tends to be employed for manufacturing components/structures which must withstand higher mechanical loads for over periods of decades.

The developers of the RELO material intend to try to identify non-critical, wet cast components, which could be manufactured using a modified RELO mixture. However, the RELO developers feel that a great deal more information concerning the long-term performance of the RELO material must be gathered before any attempts are made to use the RELO material for critical load bearing components/structures.

Taking the above concerns into account, it should be emphasized that wet-cast components make up a large part of the concrete elements used in the building sector. Therefore, if the RELO (and similar alternative binder materials) are to make the biggest impact in reducing

CO_2 emissions, then they must be developed to a level allowing the manufacture of components normally requiring wet concrete.

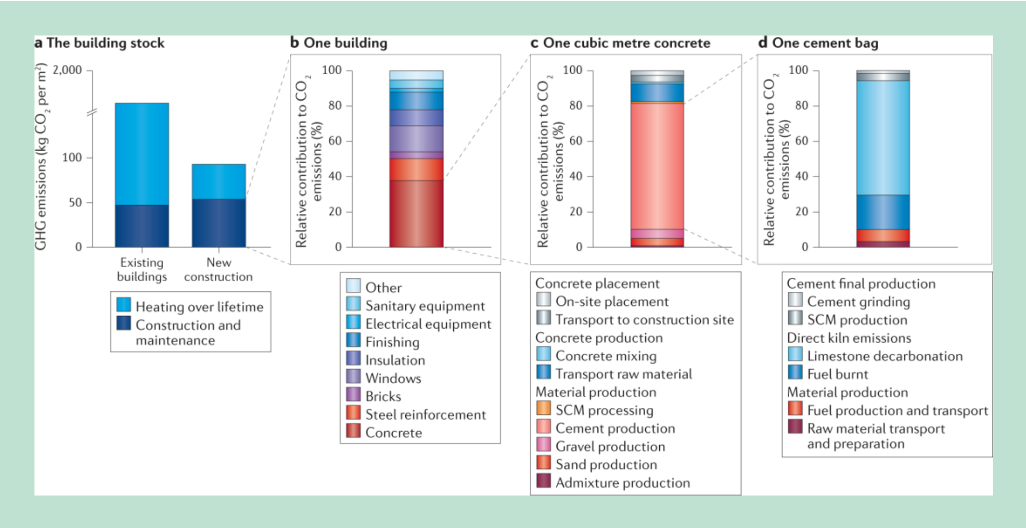


FIGURE 14. Environmental footprint of a structure at different levels [21].

25%

Of the total CO_2 emissions, for new building construction and maintenance, is related to cement production

In 2020, G. Habert published a large study of the breakdown of CO_2 emissions from the finished construction to the individual components in the concrete, which paints a clear picture of cement's impact on the overall CO_2 emissions. 38% of the total CO_2 emission associated with construction is related to the concrete, of which around 70% comes from the cement. This emphasized the potential of the RELO material, if it can guarantee long-term performance and suited as a wet cast material.

4.3 Environmental Product Declaration

To enable further evaluation of the environmental aspects of using RELO material, it is important that the RELO based concrete formulations are subjected to some form of independent environmental product declarations before being marketed.

Something that has become more important in 2023, with the new requirements in the building regulations, which demands climate calculation and complies with CO_2 limits for new construction over 1000 m^2. A demand that in 2025 will be updated and include new construction under 1000 m^2.

12

Kg CO_2-e/m²/yr.

2023 Limit values for new construction over 1000 m2

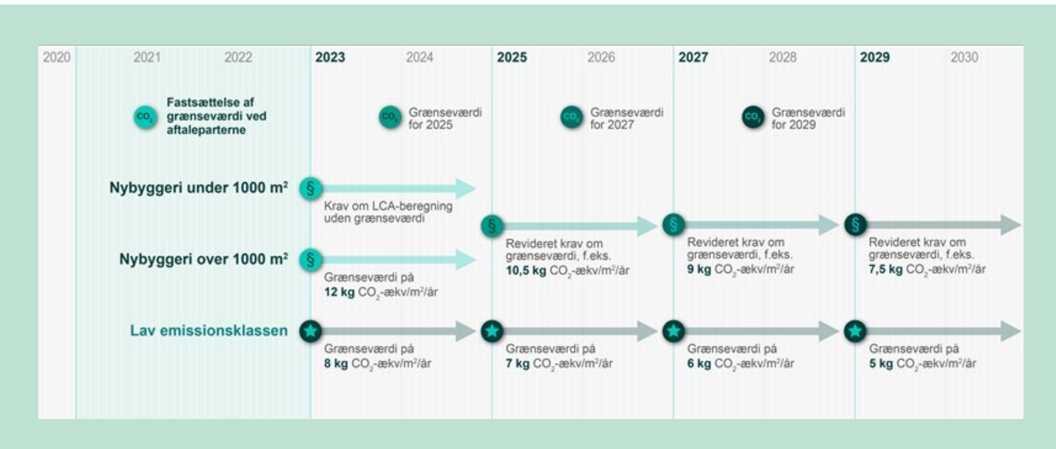


FIGURE 15. Timetable for buildings climate impacts (CO_2) and how it will gradually be tightened towards 2030 [17].

In 2021 the European Commission published a document EU 2021/476 outlining the criteria which “hard covering materials” must meet to be awarded the EUs, so called, Ecolabel. The main purpose of creating such a label, which is awarded on a points-based system, is to allow potential end users of hard covering materials (e.g. concrete) to more easily evaluate the environmental impact of the materials they plan to employ.

It has been estimated that the time required to document all the information required and pass through the qualification procedure to receive an Ecolabel will take approximately six months. The procedure to qualify the RELO based material for an EU Ecolabel is presently being undertaken by IBF. However, it is expected that final approval for the RELO material will not be achieved until after the conclusion of the present RELO project.

5. INDUSTRIALISATION

5.1 Modification of Existing Production Equipment

The industrial trials described in this project, although successful, were carried by manually feeding the RELO material into the mixing unit of IBFs production equipment in Hedehusene. Manual feeding was necessary because IBFs production equipment was specifically designed to manufacture concrete products using Ordinary Portland Cement as a binder material. This equipment cannot presently be used to feed RELO material automatically into the mixing unit. In addition, IBF does not possess enough silos to store large amounts of RELO material.
It is envisaged that the first step in producing RELO based products on an industrial scale will involve modifying IBFs present production equipment so that large amounts of RELO material can be stored, automatically fed into the mixing unit and mixed appropriately before being finally transferred to the gyro-compactor.

5.2 Scaling

It is envisaged that, once IBF’s manufacturing equipment has been modified, the equipment will be used to manufacture paving stones under a range of production conditions (e.g. compaction pressure, compaction time, mixing order). The information gained from these tests will be used to establish more accurate scaling law relating the results from small scale laboratory testing and the industrial scale production tests.

Once more accurate scaling laws are established it should allow future laboratory testing to be used to quickly establish the way in which the industrial equipment must be set up to achieve a particular end result. This would mean that the relatively small amounts of material, used for laboratory testing could be used to determine the production conditions to produce batch sizes of over 2 tons.

Previously the only way to determine the correct settings for the production equipment was to use the production equipment itself to find the correct settings. This approach results in a large amount of waste concrete as the production equipment cannot be used to mix batch sizes of less than approximately 1 ton.

The results from the RELO project now allow the production equipment to be “roughly” set-up to the right conditions. Once the “rough” set-up is completed the final settings are determined by a “tuning” process involving, manufacturing a concrete batch, measuring its green properties and using the results to find the correct settings. Although this has been a step forward the establishment of accurate scaling laws should allow the industrial equipment to be set-up correctly without the need for “tuning”.

Once accurate scaling laws have been established the production equipment will be used to manufacture a range of products using mixture designs identified by laboratory testing. This should allow the industrial scale production to be further refined and enable products to be manufactured which are “tailor made” for a particular end use (e.g. products with a particular surface finish, water absorption, strength).

5.3 Validation

All paving stones manufactured using the RELO binders will be subjected to tests laid down in the various European EN standard related to paving stones (DS/EN 1339).

DS 1339

“The Standard provides for the product marking and the evaluation of conformity of the product to the European Standard.”

The purpose of the standard is to specify materials, properties, requirements such as water absorptions, freeze thaw properties as well as corresponding test methods. The standard applies to precast, unreinforced, concrete paving stones for use in trafficked areas.

The standard will be used as a basis for product marking.

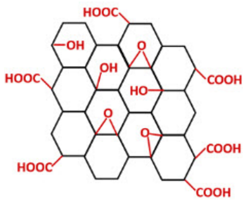
5.4 Use of Waste Materials

It is envisaged that future work will also involve exploring what other waste materials can be used to manufacture binders suitable for concrete manufacture. For example, it has been demonstrated that rice husks have a very high silica content and, when burnt, produce an ash which possesses cementitious properties well suited to concrete production. There are other plants, better suited to Scandinavia; that could potentially be burned in local heating plants to produce ashes containing large amounts silica (e.g. certain species of bamboo which will grow in northern climates). It is suggested that the potential of such plants for cement production should be explored as they would offer a much “greener” route for binder production.

6. FUTURE MATERIALS

There are materials, currently being researched, that could potentially lead to further reductions in CO_2 emissions. One of the most promising is graphene oxide. It has been reported that small additions (< 0.1% by weight) of graphene oxide to conventional Ordinary Portland Cement concrete can result in a 30-50% increase in compressive strength and a 20-30% increase in flexural strength.

To date, investigations into the use of graphene oxide to reinforce concrete has been focussed on conventional pourable/pumpable concrete. As far as the authors of this report are aware, no research has been undertaken into mixing graphene with the type of binders used to produce the components described in this report. Research into this area may show that, the addition of graphene oxide to the RELO binder, results in increases of compressive and flexural strength comparable to those described above. In which case a graphene oxide-RELO binder mix could be used to manufacture a concrete with a significantly better performance in terms of CO_2 footprint and mechanical properties than a concrete manufactured from OPC mixed with graphene oxide.



Graphene oxide (GO)
A single-atomic layered material, made by the oxidation of graphite.

Unfortunately, at present, graphene oxide is prohibitively expensive (14,000 €/ton) and until the price falls it is very unlikely that graphene oxide will be used in the manufacture of low-tech concrete components such as paving stones. However much of research efforts into graphene production is focused on developing cheap and simple production methods and it is expected that such methods will be developed in the next 5 years.

7. DISSEMINATION

In order to disseminate the results of the RELO project to potential end users those responsible for the RELO project have held meetings with a wide variety of groups including the following:

RealDania
Discussions between RELO researchers and RealDania were undertaken even before the RELO project started. These discussions focussed on trying to identify existing mortar/concrete based components whose CO_2 footprint could potentially be reduced if they were to be manufactured using a RELO type binder.

A meeting was held at RealDania's headquarters during which the RELO researchers presented the results of earlier development work on RELO type binders supported by MUDP. At this meeting, which was attended by 15 Danish architects, there was a general consensus that, in the first instance, RELO type binders should be used in the manufacture of low-tech concrete products that would not be a safety threat or result in a significant economic loss if they failed. It was after this meeting that the RELO researchers decided to focus more on using the RELO binder for the manufacture of paving stones.

WE BUILD DENMARK
Is an organisation set up by the Danish government to help develop the Danish construction industry. WE BUILD DENMARK has a number of different roles including (a) acting as a hub for the exchange of specialised information related to construction and materials used for construction, (b) business development (c) acting as a matchmaker between those working in the building industry (d) promoting sustainable construction and circular economies (e) helping in finding funding for building related projects.

In December 2022 RELO researchers held meetings with WE BUILD DENMARK during which the latest results of the RELO project were presented and the possibility of WE BUILD DENMARK finding potential end user for RELO paving stones was discussed.

Resource City, Næstved
Have established a network of local companies which can help and support each other in the transition to a circular economy. This is achieved through knowledge sharing, exchanges of experience, innovative processes and collaborative projects.

Part of the work of Resource City in creating circular economies has been to help companies to find uses for their waste products. Discussions in December 2022 between those responsible for the RELO project and representatives from Resource City were undertaken to both make Resource City aware of the work being carried out under the RELO project and to discuss the potential use of locally available waste materials (e.g. recycled concrete) as aggregate in RELO concrete.

Næstved Local Government, Center for Technology and Environment
During December 2022 a meeting was also held between the RELO concrete developers and representative from the Næstved's Local Government Building Department. The aim of this meeting was to make the Building Departments representatives aware of the RELO project and of the potential of the RELO based concrete in reducing CO_2 emissions.

MUDP Annual Report

During January 2023 those responsible for the RELO project were interviewed by a representative of MUDP. The interviewer asked, and was informed, about the latest results of the RELO project and was given a guided tour of the IBF production unit used to manufacture the first RELO paving stones under industrial conditions. The aim of the interview was to gather information for an article which is planned to be published in the 2022 MUDP annual report.

Confederation of Danish Industry

The developers of the RELO binder recently attended the “Made in (More) Sustainable Concrete” conference hosted by DI and held in Copenhagen 2022 during which new contacts with various leading, international concrete researchers were established. These new contacts included Professor John Provis, Sheffield University, UK, a key speaker at the conference and one who is widely recognised as a world authority in the area of alternative concrete research.

Build green

In the autumn of 2022, the developers of the RELO binder participated in Building Green Copenhagen 2022 in Frederiksberg, where new international contacts with German industry were established. These new contacts have led to new ideas and focus on waste materials, close to the Danish-German border, which have potential in relation to the business potential in the secondary market.

8. WORKS CITED

[1] J. Timperley, "Carbonbrief," 2018. [Online]. Available: https://www.carbonbrief.org/qa-why-cement-emissions-matter-for-climate-change/.

[2] R. Andrew, "Global CO2 emissions from cement production," *Earth. Sci. Data, ,* pp. 195-217, 2018.

[3] R. e. a. Walker, "Effects of extraction of marine sediments on the marine environment 2005-2011, Report No 330," International Council for the Exploration of the Sea, Copenhagen , Denmark, 2016.

[4] S. Evans and S. Yeo, "Carbonbrief," 2015. [Online]. Available: https://www.carbonbrief.org/analysis-the-final-paris-climate-deal/.

[5] IEA, "Technology Roadmap - Low carbon transition in the cement industry," Internstionsl Energy Agency, Paris, France, 2018.

[6] UNFCCC, "THE PARIS AGREEMENT," PARIS , 2016.

[7] J. L. Provis, *Innovation in Cements: Can We Meet Future Construction,* Copenhagen: University of Sheffield, UK, 2022.

[8] Anon, "Energy Efficient Buildings PPP: Multi-annual roadmap and longer term strategy," European Commission, Brussels, Belgium, 2010.

[9] Anon, "EU Energy and Transport In Figures Pocketbook," European Commission, Brussels, Belgium, 2011.

[10] C. S. P. N. J. T. N. Chatziaras, "Use of alternative fuels in cement industry," Skiathos island, Greece, 2014.

[11] R. McSweeney, "Absence of carbon capture and storage is 'biggest challenge to' 2C limit," 2017. [Online]. Available: https://www.carbonbrief.org/absence-carbon-capture-storage-biggest-challenge-2c-limit/. [Accessed 2022].

[12] N. Brevik, "Brevik CCS – World's first CO2-capture facility at a cement plant," [Online]. Available: https://www.brevikccs.com/en. [Accessed 2022].

[13] B. e. a. Koelbl, "Uncertainty in the deployment of Carbon Capture and Storage (CCS): A sensitivity analysis to techno-economic paramter uncertainty," *International Journal of Greenhouse Gas Control,* pp. 81-102, 2014.

[14] E. Williams, "The economics of direct air carbon capture and storage," Global CCS Institute, 2022.

[15] J. Davidovits, Geopolymer chemistry and applications, Saint Quentin, France: Institut Géopolymére, 2020.

[16] epddanmark, "Hvordan læses og bruges en miljøvaredeklaration (EPD)".

[17] I.-. o. Boligministeriet, "National strategi for bæredygtigt byggeri," Indenrigs- og Boligministeriet, 2021.

[18] P. H. R. Borges, "Andreasen Particle Packing Method on the Development of Geopolymer Concrete for Civil Engineering," *JOURNAL OF MATERIALS IN CIVIL ENGINEERING,* pp. 692-697, 2014.

[19] F. d. Larrard, "Concrete optimisation with regard to packing density and rheology," in *3rd Rilem International Symposium on Rheology of Cement*, Bouguenais - France, 2009.

[20] *https://www.ibf.dk/,* 2023.

[21] G. M. S. J. Habert, “Environmental impacts and decarbonization strategies in the cement and concrete industries,” *Nature Reviews Earth & Environment,* p. 559–573, 22 September 2020.

[22] M.-. o. Fødevareministeriet, “Strategi for cirkulær økonomi,” Miljø- og Fødevareministeriet, København, 2018.

RELO resumé

The production of 1 ton of Ordinary Portland Cement releases approximately 1 ton of CO_2 into the atmosphere and presently the cement industry is responsible for approximately 8% of the world's anthropogenic CO_2 emissions – a greater share than any country other than China or the US.
There is clearly a pressing need for a binder that can function in the same way as OPC but one that does not emit the same amount of CO_2 under production. The RELO binder, described in this report, is such a binder: RELO concrete has a CO_2 emission that is 53% less than that of conventional OPC based concrete and has been used to manufacture paving stones with compressive strengths of over 30 MPa and splitting strengths of approximately 5 MPa.
This report describes the development of the RELO binder which uses a number of waste/recycled materials to achieve a low CO_2 emission. Tests carried out to EN standards on concretes manufactured using the new binder are described as well as how the new binder has been employed to manufacture paving stones under industrial conditions. The report also identifies a range of other cement-based products that could potentially be manufactured using the RELO binder.
The report also includes suggestions for further material and process developments which, if implemented, could result in a material with even better properties than the RELO binder.

The Danish Environmental
Protection Agency
Tolderlundsvej 5
DK - 5000 Odense C

www.mst.dk